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FUNDAMENTALS OF MACHINES

THE AUTHORS

Charles E. Dull received his Bachelor's degree at Oberlin College and his Master's degree at the University of Chicago. His first textbook was published by Henry Holt and Company in 1918. His Modern Physics and Modern Chemistry are known by high-school teachers all over the United States. He has recently collaborated with Paul B. Mann and Philip G. Johnson in writing a three-book general-science series, Modern Science. In addition, he has written many other textbooks and workbooks. These books are products of his twenty-odd years of classroom teaching. Since 1926, he has taught in the West Side High School in Newark, New Jersey. He continues to teach physics and chemistry there, although he is now Supervisor of Science for the Junior and Senior High Schools of Newark. He has brought conversational simplicity to the writing of science textbooks, so that they require no translation for average high-school students.

Ira G. Newlin is a newcomer to the textbook writer's field. He was chosen as co-author of this book because of his reputation as a high-school science teacher. He has taught physics and chemistry for thirteen years: two years at Mount Holly (New Jersey) high school, three years at Moses Brown School (the well-known college-preparatory school in Providence, Rhode Island), and eight years in Scarsdale (New York) High School, where he is now head of the science department. Mr. Newlin took his Bachelor's degree at Guilford College, and his Master's degree in Chemistry at Haverford College.

Dull, Charles Elwood -

FUNDAMENTALS OF MACHINES

A PRE-INDUCTION COURSE AT THE FOUNDATIONAL LEVEL

Prepared at the request of the War Department and the U. S. Office of Education in conformance with official pre-induction training course outline PIT–102.

NEW YORK
HENRY HOLT AND COMPANY

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Preface

The War Department, through the U. S. Office of Education, has asked the nation's high schools to offer pre-induction courses to the young men who are soon to go into the armed services. You have undoubtedly read the outlines for these courses prepared jointly by the War Department's Pre-Induction Training Section, Civilian Personnel Division, Services of Supply, and the U. S. Office of Education. These outlines (PIT–101, PIT–102, PIT–103, etc.) were developed by Army curriculum specialists and practical classroom teachers.

"For about 20 per cent of our boys in and out of school," the PIT bulletins say, "a war-applied course in physics and mathematics will give excellent background for continued specialization at the college level. These boys will constitute a reservoir from which many of our officers will be drawn."

But what about the remaining 80 per cent? For them, the bulletins say, "more specific fundamental courses are needed. A large variety of such courses is possible. However, critical shortages would indicate that the following courses can make the greatest immediate contribution to the flow of trained manpower:

"*Fundamentals of Electricity;*
"*Fundamentals of Machines;*
"*Fundamentals of Shopwork.*"

Representatives of the War Department and the U. S. Office of Education approached the textbook publishers in mid-October of 1942 with the request that they implement with books these pre-induction courses — new books written especially for the purpose and produced in time for use in early 1943. Henry Holt

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and Company undertook to produce the three *fundamentals* books listed in the quotation above. They left to technical publishers the preparation of more advanced textbooks for the courses at "beginning specialization" and "operational skills" levels. They asked us — Charles E. Dull and Ira G. Newlin — to construct this *Fundamentals of Machines.*

We wrote it in strict conformity with PIT–102, as you will see if you examine our Table of Contents. The Army curriculum specialists and teachers who, working under the direction of the War Department and the U. S. Office of Education, devised the course numbered PIT–102 gave us generously of their help and counsel as we wrote our book.

Since you have read these PIT outlines, we need not repeat here the statements of Secretary of War Stimson, Under Secretary of War Patterson, and U. S. Commissioner of Education Studebaker — all of which appear in the outlines — written in support of pre-induction courses in high schools. But we should like to report once again the remarks of Lieutenant General Brehon B. Somervell made last August to a large audience of school and college officials:

"Our Army today is an army of specialists. Out of every 100 men inducted into the service, 63 are assigned to duties requiring specialized training. We aren't getting those 63 specialists through the induction centers. Modern warfare dictates that we must have them." In those four sentences, General Somervell stated the reasons for high-school pre-induction courses. This particular course, *Fundamentals of Machines*, opens the way to 226 specialist assignments in the Army.

This is a one-semester course for grades 11 or 12, planned for 90 periods of teaching. We have tried to write simply, as for the boy untrained in the sciences. We have used plenty of homely illustrations, and moved usually from the familiar to the unfamiliar. We have provided diagrams and other illustrations in the profusion characteristic of Holt science books. We have inserted demonstrations in the text and have supplied laboratory exercises at the end of the text. At the ends of chapters, we have put self-testing exercises, vocabulary drills, thought-provoking questions, and problems. Remembering that many boys who take this pre-induction course may be rusty in their mathematics, we have provided in an appendix a simple mathematics refresher. And of course there are at the end of the book all the more useful tables needed in a study of mechanics.

It has been impressed upon us that some will teach this pre-induction course in mechanics who are not trained physics teachers. We bore that in mind while writing the text and constructing the demonstrations, experiments, questions, and problems. And we have made also a teachers' manual, listing the equipment needed for this course, suggesting ways of teaching or demonstrating this and that, and giving all answers to problems.

January, 1943

C. E. D.
I. G. N.

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FUNDAMENTALS OF MACHINES

Introduction

THE MACHINE, MECHANICS, AND THE MECHANIC

What is a machine? A machine is a device which is used to transfer energy or to convert one kind of energy into another kind. The machine is so important in the world today that our civilization has been called the machine age. Everywhere, in peace and in war, at home and on the battle front, on land, at sea, and in the air, machines save our energy, or our strength, or our time. With them we have learned not only to use our own strength more effectively, but also to make use of the force of animals, water, wind, heat, and electricity, in doing our work. Whether the device which we use is as simple as a baseball bat, a hammer, a saw, or a door key, or as complex as a typewriter, an electric motor, or an airplane, it is called a machine.

What is a mechanic? A mechanic is a person who knows how to construct, repair, and use machines. He works with matter, for machines, like all other things which have weight or occupy space, are made of some form of matter.

What is mechanics? Mechanics in the broadest sense of the word is the science, or knowledge, of the construction and use of machines. Today we use the word with the particular meaning of knowledge of force, motion, and stress, without reference to any particular substance.

I

The Mechanic Works with Matter

A. WHAT IS MATTER?

1. MOLECULAR THEORY

Examples of matter. Wood, iron, copper, glass, and salt are all examples of matter. Liquids and gases are also examples of matter. Any substance that can be weighed or that occupies space is called *matter*. Invert a drinking glass, force it into a pail of water, and the air in the glass prevents the water from filling it. This illustrates the fact that a gas, for air is a gas, is just as real a form of matter as is a stone or a block of wood, or water. You can illustrate the same point with the tires on your car. The tires are filled with air which holds them in shape. The tire flattens when the air is allowed to escape through a leaking valve or a puncture. It is clear that the escaping gas must take up some room in the tire, and, consequently, is a form of matter.

Matter is made up of molecules. Theoretically, a piece of marble or chalk may be broken into two pieces, those two into four, and so on to infinity. In reality, no kind of matter can be subdivided beyond a certain point without losing its identity. Water may be split up into two gases (hydrogen and oxygen), but when this happens it is no longer water; it loses its characteristic properties. The smallest particle into which matter can be subdivided without destroying its *characteristic* properties is called a *molecule*.

No one has ever seen a molecule; these particles are so small that the best microscope fails to reveal them. Suppose that a drop of water were magnified until its diameter equaled that of the earth; if its molecules at the same time were correspondingly increased, it is estimated that they would appear about the size of baseballs. It has been estimated that one liter (a trifle more than a liquid quart) of air contains 27×10^{21} molecules. If you will write the figure 27 followed by 21 ciphers you will realize just how tiny each particle must be. You may inhale, in one deep breath, about four times that number of molecules.

If you inflate an automobile tire to a pressure of 30 lb. per sq. in., you are only pumping more air molecules into the tire. It is possible to pump into such a tire two times as many molecules as it had contained, three times as many, ten times as many, or even more than that if the tire is strong enough so that it will not burst under the increased pressure. We are crowding the molecules together more closely, or reducing the distances between them. Despite the enormous number of molecules present in such a tire, you must decide, as you crowd so many more into the same space, that they could not have been even relatively near neighbors.

We may change matter in any way we see fit, but if we do not break up the molecule, we have a *physical change.* In the science of physics, *the molecule is the unit of matter.*

The molecules are made up of even smaller particles called *atoms.* If we break matter up into its atoms, we have a *chemical change.* (Physical and chemical changes are described in greater detail on pages 5–6.) *The chemist's unit of matter is the atom.* In the laboratory, the chemist builds up new molecules from atoms, he breaks up complex molecules into atoms, or he rearranges the atoms in the molecule. By the use of the X rays, scientists have learned how the atoms are arranged in certain molecules. For example, a molecule of table salt has the latticed structure shown in Figure 1–1. The black and the white particles represent atoms of sodium and chlorine, of which the salt is composed.

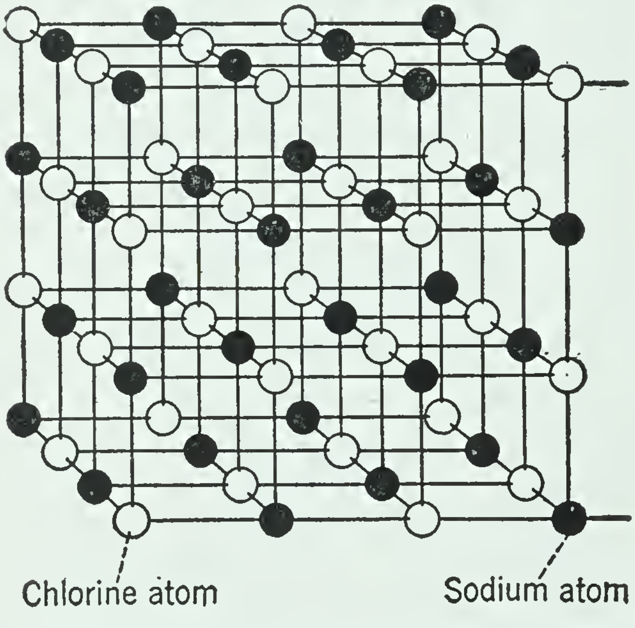


FIG. 1–1. A crystal of common table salt is composed of sodium and chlorine atoms arranged in a latticed structure.

Matter exists in three different states. Solids, liquids, and gases represent the three *states* of matter. One state of matter may be changed to another, as when iron, a solid, becomes liquid in the terrific heat of the blast furnace. Such changes as this in the *state* of matter will be discussed in a later chapter. Solids have a definite volume and a definite shape; liquids have a definite volume but they take the shape of the containing vessel; gases have neither a definite volume nor a definite shape. Gases not only take the shape of the containing vessel, but they expand and fill the vessel, no matter what its volume. In solids, the molecules cling quite firmly together and do not change their relative positions readily; hence solids have a definite shape. In liquids, the attraction between the molecules is less, and they slide over one another quite readily. In gases, the molecules move so freely that they tend to separate; hence the indefinite expansion.

It is rather difficult to classify a substance like sealing wax, which breaks when struck a sharp blow, but flows under pressure. Both liquids and gases flow freely; hence both are called *fluids*, from a Latin word which means *to flow*. A liquid that flows easily is said to be *mobile;* such a substance as tar, which flows slowly, is said to be *viscous*.

Since heat causes the molecules to move more rapidly, an increase in temperature tends to make matter more fluid; heat promotes fluidity. Motor oils that are quite viscous in cold weather become quite mobile in summer. In fact, an increase in temperature may convert a solid first into a liquid, and then into a gas or vapor. Water readily changes to ice, a brittle solid, if cooled to 32° F.; when its temperature is increased to 212° F., water is converted into steam, which is a gas or vapor. Even such a solid as iron can be melted or even changed to a gas by heating it to a very high temperature.

2. LAW OF CONSERVATION OF MATTER

Physical and chemical changes in matter. Many changes are constantly taking place in matter. Wood burns; water freezes;

salt dissolves in water; milk sours. These are merely examples of hundreds of changes occurring daily. Changes in matter are of two kinds, *physical* and *chemical.* If the identity of a substance is not lost, the change is *physical,* as we have seen; if a new substance with new characteristic properties is formed, the change is *chemical.* When milk sours, it loses the characteristic properties of sweet milk. Such a change is chemical. The burning of wood is also a chemical change. When water freezes, its molecules are not broken up or rearranged. An increase in temperature converts it to its former state. Such a change is physical. *Physics* deals with *physical* changes in matter; *chemistry* deals with *chemical* changes.

Matter is indestructible. If we weigh a block of ice, melt it, and weigh the water which is formed, we find that there is no change in weight. *No matter has been lost.* The chemist may let a piece of iron rust, and then recover the iron from the rust. It will have the same weight as the original piece of iron. We may change the form of matter or change its state, but we cannot destroy it. While we cannot destroy matter by means of either a physical or a chemical change, neither can we create matter. Hence the total quantity of matter in the universe is the same today as yesterday. The fact that matter cannot be created or destroyed is usually called the *law of the conservation of matter.*

Demonstration. Does a chemical reaction cause a change in weight of the matter involved? Place two beakers, one containing a barium chloride solution and the other a sodium sulfate solution upon the platform of a beam balance. Counterpoise the beakers with weights on the other platform. Pour the contents of one of the beakers into the other. Replace the empty beaker. Is there any evidence of chemical change? Is there any change in weight?

B. GENERAL PROPERTIES OF MATTER

Matter has properties. Steel is hard; hence it makes good cutting tools. Aluminum transmits heat readily; hence it is suitable for cooking utensils. Different substances have different properties. Weight, mass, volume, inertia, and impenetrability for example, are common to all substances. They are called *general* properties. There are also many *special* properties which are common to certain substances only. We identify substances by studying their special properties. The use to which a substance is put depends upon its special properties. Since steel is hard and tin is soft, we make knife blades of steel instead of tin. We use diamonds to cut extremely hard rock because diamond is one of the hardest substances known. The color, odor, taste, and solubility of a substance would also be called its properties. All the properties just mentioned are classified as physical properties. To say that wood or coal burns is a statement of a chemical property. In a study of machines we are primarily concerned with physical properties of matter. We shall first discuss its general properties.

1. WEIGHT

What two things determine weight? If we release a ball, it falls to the ground. We say that it is attracted to the earth by the force of gravity. When we find the weight of an object, we are merely measuring the attraction of the earth for that body. The weight of an object depends upon two things: (1) the quantity of matter that it contains; (2) the measure of the earth's attraction for it. The first does not vary, for an iron ball will contain the same quantity of matter at *any* place, either at the surface of the earth or 100 miles from the surface. But the second factor does vary, for the earth's attraction for a body will be less upon a mountain than in a valley, and an object will weigh less 100 miles above the surface of the earth than it does at the surface. *Weight is defined as the measure of the earth's attraction for a body.*

2. MASS

The quantity of matter in a body does not vary. Suppose that we have a certain object. It contains a definite quantity of matter. *The measure of the quantity of matter which a body contains is called its mass.* The mass of a body does not vary. We may squeeze a body and reduce its volume, but the quantity of matter in it remains the same. If we could take the body up on a high mountain, or even to the moon or the sun, its mass would remain the same because it would still contain the same number of molecules and therefore the same quantity of matter.

Although the units of weight will be considered in Chapter II, we should note here that the standard unit of mass, the kilogram, *weighs* one kilogram (or 2.204622 pounds) only at sea level. Two such units would balance on an equal-arm balance at any elevation, hence their mass remains constant; but the earth's attraction for each decreases with increased altitude. Therefore, their weight diminishes as their distance from the earth's center increases.

Demonstration. Do equal volumes of different substances have the same mass? Weigh a strip of lead metal. Cut a piece of soft pine wood to the same length, width, and thickness as the strip of lead, and weigh it. How do the two weights compare?

3. VOLUME

All solids, liquids, and gases have volume. If matter occupies space, it must have length, breadth, and thickness. In other words, matter has *volume.* When you studied arithmetic, you learned how to find the volume of rectangular solids *directly* by obtaining the product of their length, breadth, and thickness. By the use of an *indirect* method in the laboratory, we shall learn how to find the volume of any solid, no matter how irregular it may be. Liquids and gases also occupy space and have the property of *extension,* or volume.

Demonstration. How can the volume of solids be found? Fill two graduated cylinders (100 cc. capacity) with water to the 50 cc. mark. Drop into one cylinder a strip of lead 2 cm long. Drop into the other cylinder a strip of lead, of the same width and thickness, 4 cm. long. Note the level of the water in each cylinder. From the difference in water levels compare the spaces occupied by the two volumes of lead.

4. INERTIA

Bodies in motion tend to keep moving; bodies at rest tend to remain at rest. You board a car or a bus, find the seats all occupied, and grab a strap for support. When the car starts forward suddenly, you are jerked backward. Your body was at rest while the car was standing still, and so your body had a tendency to remain at rest. Your body was *inert,* or *inactive,* and the car seemed to be trying to go forward and leave you at rest. If the car stops suddenly, you lurch forward. Your body was in motion with the car, and, when the car stops, your body tends to keep on moving. Matter has no ability in itself to move or to stop moving. Matter is *inert,* which means that it is inactive or lazy. Since all matter has the property of inertia, *bodies in motion tend to remain in motion and bodies at rest tend to remain at rest.* It requires some force, such as a push or a pull, to overcome the inertia of a body and set it in motion or stop it when it is in motion.

There are many examples of inertia. A car going 40 miles per hour strikes a tree. The driver is likely to continue on forward and be thrown through the windshield. If you leap from a rapidly moving car, you are likely to fall in the direction in which the car was moving, because inertia pushes your body forward, while your feet are stopped by the friction of the pavement.

Sometimes inertia is put to *practical use.* You stand in front of a furnace with a shovelful of coal. As you swing the shovel and coal forward toward the furnace door, both the shovel and the coal are in motion. Then you stop the shovel, but, on account of its inertia, the coal continues on into the furnace. In running a sewing machine, the operator pushes downward first with the toe and then with the heel. The rim of the band wheel has enough inertia to keep the machine in smooth, steady operation between such successive pushes. The flywheel on the crankshaft of a gasoline engine has a heavy rim to supply the inertia needed to keep the engine running smoothly, although the explosions which drive the engine are intermittent and not continuous.

Demonstration. What property is common to objects in motion and objects at rest? Pile several wooden blocks on a board to which a string is attached. Cautiously pull the string until the board with its pile of blocks is moving uniformly along the smooth surface of a table or the floor; then suddenly stop. Repeat the demonstration, but instead of starting cautiously give the board a sudden sharp pull. Compare the results of these two tests. Place a tumbler near the edge of a piece of paper. Suddenly withdraw the paper. Did the tumbler overturn? Explain.

5. IMPENETRABILITY

No two bodies can occupy the same space at the same time. One car must give way to another at a street intersection. Both cars cannot cross at once or be in the same spot at the same time. We cannot pour water into a bottle through a narrow opening unless we make some provision for the air inside the bottle to escape. The air takes up room. A nail driven into a board does not penetrate the wood, but it pushes the fibers of the wood aside. From such examples, we must conclude that *no two objects can occupy the same place at the same time,* because *matter is impenetrable.*

We can make use of the property of *impenetrability* to find the volume of an *irregular* solid. We put into a graduated cylinder enough water to cover the irregular object and note the mark to which the water rises, as in Figure 1–2. As we then lower the solid into the water, the displaced water will rise to a higher level. The difference between the two graduation marks equals the volume of the water displaced. The volume of the water displaced just equals the volume of the irregular solid. We can find the volume of any insoluble, nonporous solid by this method.

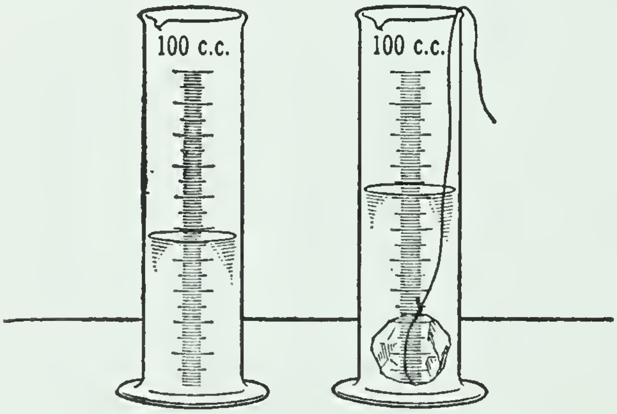


Fig. 1–2. Because the solid is impenetrable, it displaces its own volume of water.

Demonstration. Do gases have the property of impenetrability? Stuff a handkerchief into the bottom of a glass tumbler. Invert the tumbler into a battery jar, or other container, filled with water. Does the handkerchief become wet? Explain. Fit a bottle with a one-hole stopper. Insert a glass funnel into the stopper and try filling the bottle with water. Repeat, using a two-hole stopper, with one hole open. Compare the results obtained with the two-hole stopper and the one-hole stopper, and explain.

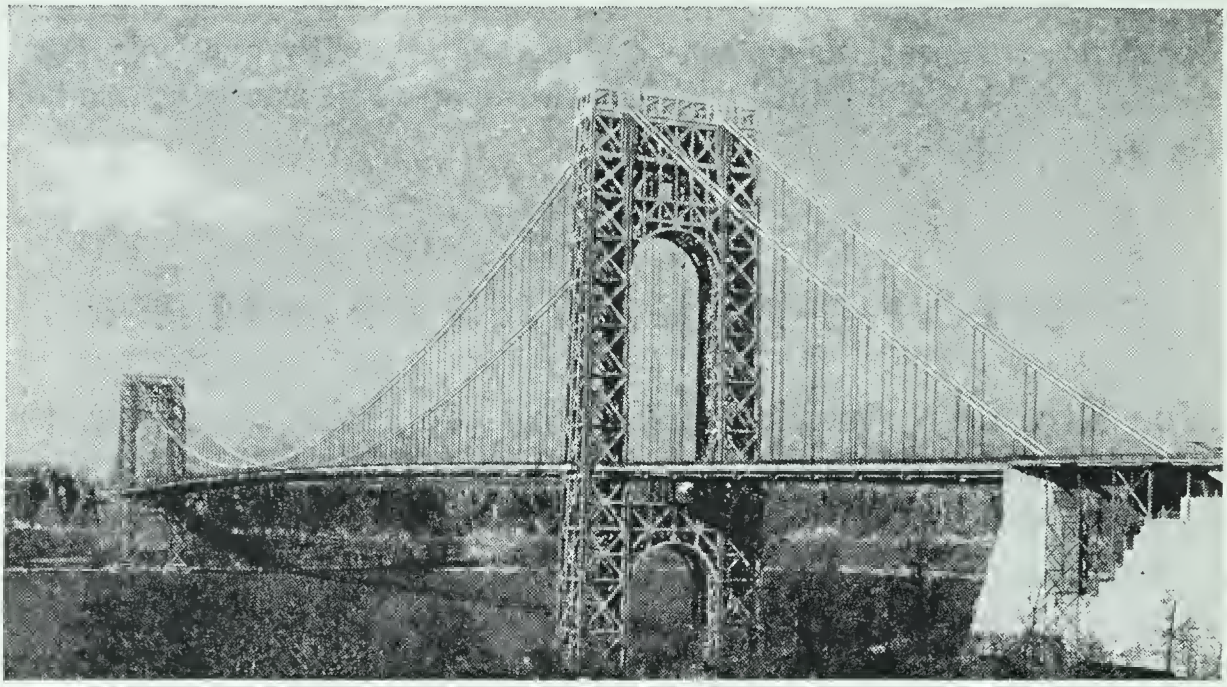
C. SPECIFIC PROPERTIES OF MATTER

You have been studying the *general* properties of matter, the properties which all forms of matter have in common. But these properties do not distinguish one form of matter from another. In this section you will consider certain *special* properties of matter, properties that help us to distinguish one form of matter from another. Glass, for example, can be recognized because it is brittle and transparent. Some metals are malleable, others are hard or soft. Each kind of matter has its own particular characteristics which make it different from any other kind. Let us note four of the many special properties of matter.

1. TENACITY

Tenacity means strength to resist breaking by pulling. By laboratory test we find that a silk thread is stronger than one of cotton, if both have the same diameter, or the same cross-sectional area. A copper wire is more easily broken than one of steel. We say that steel is more *tenacious* than copper. When we ride in an elevator, our safety depends upon the *tenacity* of the cable. The tenacity of any material, or its *tensile strength*, is measured by the force needed to break a rod or wire of that material whose cross-sectional area is one square inch. (See Appendix A, Table 6.) It takes a load of 300,000 lb. to break a bar of high-grade steel whose cross-sectional area is one square inch.

In construction work such as that on bridges the magnitude of the total load to be supported and the tensile strength of the material to be used determines the size or cross-sectional area of the supporting cable. The steel cables that sustain the weight of the



Courtesy of the Port of New York Authority

FIG. 1–3. With its approaches, the George Washington Bridge is 8700 feet in length. The steel cables, which are 36 inches in diameter, support the weight of the bridge.

George Washington Bridge are 36 inches in diameter. (See Fig. 1–3.) A single span of the Golden Gate Bridge of San Francisco stretches over 4200 feet of water.

Increasing the temperature of a metal weakens its tensile strength. Metals suffer from *fatigue*, too. If a load is held by a cable for a long time, the cable may eventually break under the load which it held safely at first.

DEMONSTRATION. Do all materials have the same tensile strength? Select a piece of No. 28 copper wire and another of aluminum of the same size. With a pair of pliers in each hand seize each end of the copper wire and attempt to pull it apart. Repeat with the aluminum wire. Note the results in each case. Repeat the demonstration using piano wire of the same size. Is the tensile strength the same for each wire?

2. DUCTILITY

Metal is ductile if it can be drawn out into a wire. Suppose that one end of a copper rod is pointed so that it will pass through a tapering hole in a steel plate or a die. Suppose then that the small end is fastened to a wheel which, as it turns, pulls or draws the rod through the opening. Thus its diameter is reduced and its length increased. A metal that can be drawn into wire in such a manner is said to be *ductile.* Gold, silver, platinum, and iron are other examples of ductile metals.

Wires of very small diameter are often made by drawing the metal through a tiny hole drilled in a chip diamond. Such diamond dies are used for making the extremely fine filaments for use in electric-light bulbs. The metal used is tungsten, and it can be drawn to a diameter which is less than one-sixth that of an average human hair. Platinum, the most ductile of the metals, has been drawn into wires only 0.00003 inch in diameter. At high temperatures glass is very ductile. Quartz has been spun into threads so fine that it is impossible to see them with the naked eye.

DEMONSTRATION. Do all metals possess the quality of ductility to an equal degree? Select a piece of copper wire and another of common picture wire of the same diameter. Point one end of each wire so that it will pass through a tapering hole in a steel plate or die. With a pair of pliers pull the copper wire through the hole in the plate or die. Note the results. Next, pull the picture wire through the hole and note the results. Compare the results with those obtained with the copper wire. Does copper possess the property of ductility to a high degree?

3. MALLEABILITY

Metal is malleable if it can be pounded or rolled thin. Iron, copper, lead, aluminum, platinum, and gold may be hammered or rolled into sheets. (See Fig. 1–4.) Such metals are said to be *malleable.* Gold is so very malleable that it has been beaten into sheets so thin that it would take 250,000 to make a pile one inch high. It would require about 1000 such sheets to equal in thickness a single leaf of this book. Such thin sheets of metal are translucent; that is, some light can pass through them. Figure 1–5 shows a press for working steel ingots. Some large presses for making armor plate exert a force of 14,000 tons.

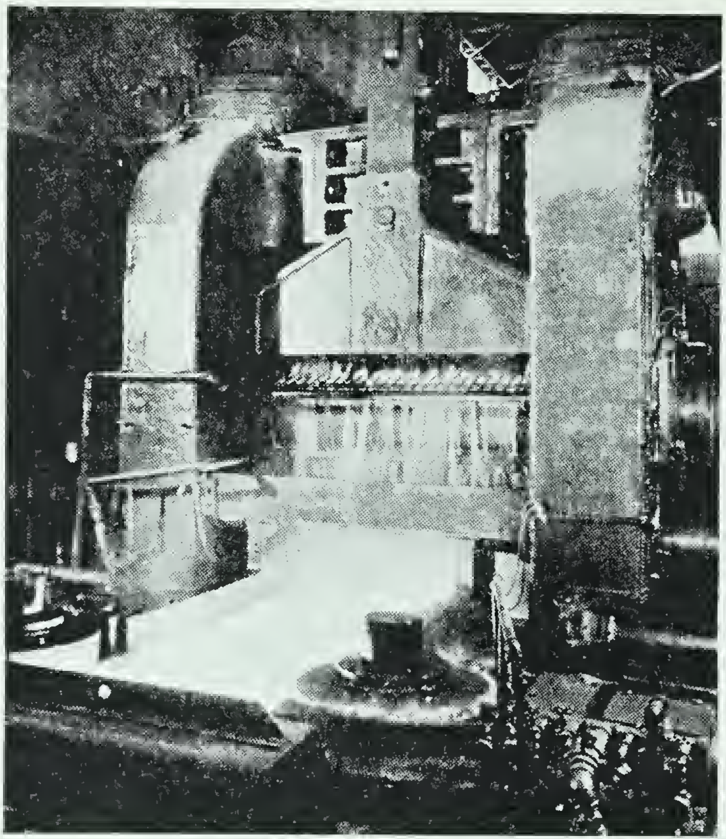
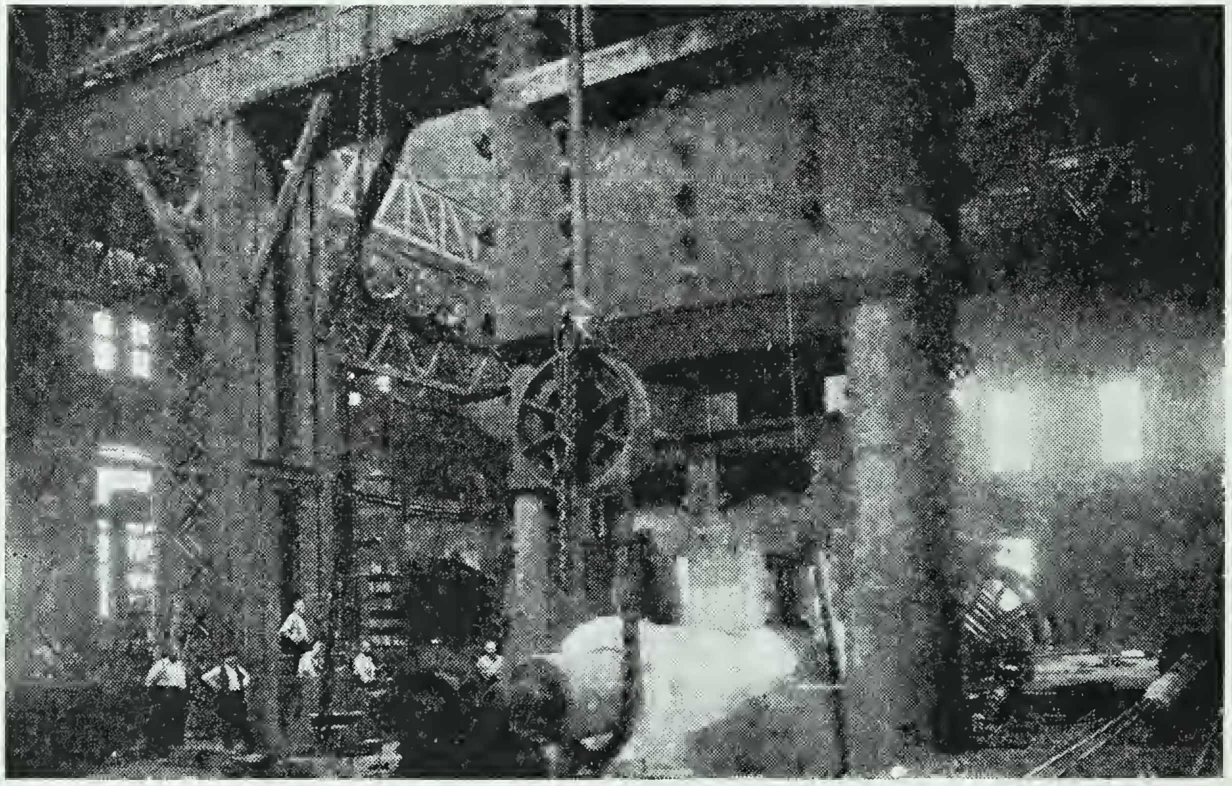


Fig. 1–4. Huge rolls are able to squeeze a white-hot bar of steel thinner and make it longer, like rolled dough, because heat makes steel more fluid or malleable.

Courtesy of the United States Steel Corporation



Courtesy of the Bethlehem Steel Company

Fig. 1–5. White hot and malleable, steel may be rough-hammered or pressed into the approximate shape desired. This treatment also removes air bubbles and certain molten impurities trapped within the metal.

Demonstration. How do lead, steel, and copper compare with respect to malleability? Pound a piece of lead with a hammer until it assumes a flat shape. Try to do the same with a piece of steel, then with a piece of copper. Note the degree of malleability of each. How do they compare?

4. HARDNESS

A substance is hard if it cannot easily be scratched or worn down. With a sharp piece of copper you can scratch lead. With a piece of steel you can scratch copper. With a diamond you can even scratch glass or steel. We say that copper is harder than lead, steel harder than copper, and diamond harder than steel. When you scratch matter you are actually separating the molecules in it. Hardness, then, is the resistance of the molecules of a substance to separation by force.

The hardness of some substances, such as steel, is increased by sudden cooling from a red-hot state. If the steel is then reheated and allowed to cool slowly it becomes tougher and less brittle. Such heat treatment is called *tempering.* Glassware is cooled slowly to make it less brittle. This process is called *annealing.*

You must not confuse hardness and brittleness. A substance that is easily broken is brittle. Glass, for example, is hard and brittle, while steel is hard and tough.

In general we call a substance *hard* if it cannot be easily scratched or abraded; that is, worn off by rubbing or by friction. The term *hard,* therefore, is only a relative one. When two substances of unequal hardness are rubbed together, the harder always wears away the softer the more rapidly, unless the soft substance is driven at a high velocity. Hard substances, like sand, emery, Carborundum, and diamond dust, are used extensively for cutting, grinding, and polishing.

Demonstration. What is the relative hardness of aluminum, copper, steel, lead, and glass? Take a piece of glass and a glass cutter. Of what substance is the roller on the glass cutter made? Mark the glass with the cutter. What is the result? Mark the glass with a diamond, if one is available, and note the results. Now, using pieces of aluminum, copper, steel, lead, and glass, rub the edge of one substance against the surface of another. Note the relative hardness of each metal.

SUMMARY

1. A mechanic is a person who is skilled in the construction, repair, and use of machines.

2. Machines are devices with which energy can be transferred or transformed.

3. Matter is anything which has weight or which occupies space.

4. Matter is made up of very small particles called molecules. The molecule, which is the unit of matter in physical change, is made up of atoms. The atom is the unit of matter in chemical change.

5. As the result of a physical change a substance does not lose its characteristic properties; a chemical change causes a substance to lose its identity.

6. Matter exists in three states: solids, liquids, and gases. Solids have a definite volume and a definite shape; liquids have a definite volume, but they take the shape of their container; gases have neither a definite volume nor a definite shape.

7. Weight, mass, volume, inertia, impenetrability, extension, and indestructibility, are properties common to all matter. Such special properties as ductility, malleability, tenacity, hardness, and brittleness are peculiar to certain substances.

How many of the following terms can you define or explain?

Machine
Mechanic
Mechanics
Matter
Molecule
Physical change
Chemical change
Atom
Mobile
Weight
Mass
Inertia
Impenetrability
Tenacity
Ductility
Malleability
Hardness
Tempering

SELF-TESTING EXERCISES

Answer These Questions

On a separate sheet of paper numbered from 1 to 6 write the letters for the phrases that answer the following questions correctly.

1. Of what is the molecule the unit? (*a*) weight; (*b*) volume; (*c*) matter; (*d*) tenacity.

2. Which of these statements is true about matter? (*a*) It is anything that can be seen; (*b*) it is anything that has weight; (*c*) it is anything that is ductile; (*d*) it is anything that is destructible.

3. What do we have if we break matter up into its atoms? (*a*) a chemical change; (*b*) an explosion; (*c*) a physical change.

4. Which property is illustrated by the fact that a stone displaces a volume of water equal to its own volume when submerged? (*a*) solubility; (*b*) hardness; (*c*) tenacity; (*d*) impenetrability.

5. What do we do when we increase the temperature of a metal? (*a*) decrease its length; (*b*) decrease its tensile strength; (*c*) decrease its weight; (*d*) increase its hardness.

6. What do metals sometimes suffer from? (*a*) fatigue; (*b*) disease; (*c*) lead paint.

COMPLETE THESE STATEMENTS

On a separate sheet of paper numbered from 1 to 13 write the words needed to fill correctly the blank spaces in the following sentences.

A device which converts one kind of energy into another is a ..(1)... The science of machines is known as ..(2)... Molecules are made up of smaller particles called ..(3)... In the melting of ice, water is changed from the ..(4).. state to the ..(5).. state. The law of conservation of matter states that matter can neither be ..(6).. nor ..(7)... The measure of the earth's attraction for a body is called ..(8)... Some force is necessary to overcome the ..(9).. of a body, to set it in motion or to stop it when it is in motion. When we cross a suspension bridge, our safety depends upon the ..(10).. of the cables of the bridge. The ..(11).. of a metal determines the fineness of the wire into which it can be drawn. In some metals a heat treatment called ..(12).. can be used to regulate hardness and toughness. An example of a very malleable metal is ..(13)...

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 8 write a T *or an* F *to show whether each statement is true or false.*

1. Machines are a means of creating energy.
2. A viscous liquid flows easily.
3. The mass of a body remains the same at all altitudes.
4. In all chemical changes some matter is destroyed.
5. In studying machines we are primarily interested in chemical properties of matter.

6. Strength and toughness of a substance are called physical properties.
7. The quantity of matter in a body and the distance from the center of the earth are two factors which determine the weight of the body.
8. The flywheel of an engine makes use of its inertia.

QUESTIONS

1. Name three physical changes and three chemical changes.
2. Could you find the volume of a lump of sugar by using the indirect method described on page 10? Explain.
3. What two difficulties would you encounter in trying to find the volume of a piece of cork by the method described on page 10?
4. Is it correct to say that wood can be destroyed by burning it? Explain.
5. Is it an exception to the general property of impenetrability when we drive a nail into a board or push a needle through a piece of cloth? Explain.
6. Sometimes water pipes jar or vibrate when the water is turned off suddenly. Explain.
7. How is the principle of inertia utilized in beating or shaking a rug or carpet?
8. How do we make use of inertia in shoveling coal or snow?
9. Mention two practical applications of inertia. Mention two examples of the property of inertia that are of no practical value.
10. Explain why shaking or jarring a tree will bring down apples, nuts, etc.
11. Why does a heavy flywheel cause machinery to run smoothly?
12. Why does it require more force to start a car than it does to keep it moving?
13. Give reasons why it is illegal to park motor trucks on bridges.
14. Why should one face forward when alighting from a car or bus?
15. How does heating a steel cable affect its tensile strength or its tenacity?
16. In Figure 1–6 the segment of string supporting the ball is cut from the same piece as the segment attached below the ball. If you pull with a quick jerk at *A* the string will break below the weight. If you pull steadily at *A*, the string will break above the weight. Explain.

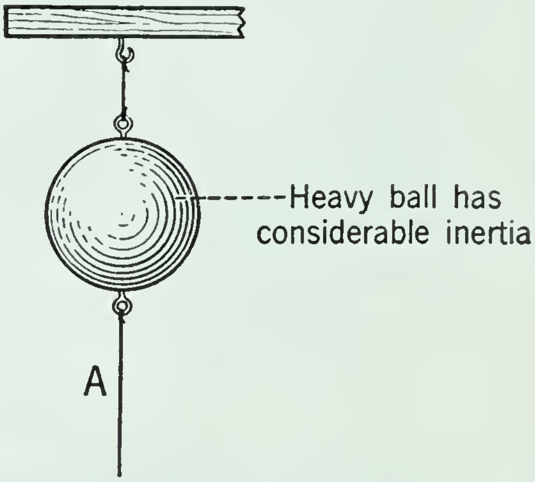


FIG. 1–6. The heavy ball has considerable inertia. (Question 16.)

II

How We Measure Matter

A. METRIC AND ENGLISH SYSTEMS

1. UNITS OF LENGTH, AREA, AND VOLUME

There are different systems of weight and measurement. From earliest times, systems have been in use for weighing objects and for measuring them.

No doubt you are more or less familiar with the *English system.* You know the number of inches in one foot, the number of feet in one yard, the number of ounces in one pound, and the number of quarts in one gallon. It is quite possible, however, that you have forgotten the number of square yards in a square rod, or the number of cubic inches in one gallon. Some figures which you may need to use are given in Appendix A.

The *metric system* originated in France at the time of the French Revolution. It is a decimal system similar to the table for United States money. If the cumbersome English system were abolished, any average pupil could learn the metric system in one lesson, because there are only three words and a half dozen prefixes necessary. The *meter* is the unit of *length;* the *liter* is the unit of *capacity;* and the *gram* is the unit of *weight.* The subdivisions of each one of these units comes from the Latin, as: *milli,* 1/1000; *centi,* 1/100; and *deci,* 1/10. Observe that these differ little from the mil, cent, and dime used in our monetary table. The multiples for each of the units in the metric system come from the Greek prefixes: *deka* or *deca,* 10; *hekto* or *hecto,* 100; and *kilo,* 1000. The metric system is used more or less exclusively in all civilized countries except Great Britain and the United States, and it is used by scientists in all countries.

The metric tables. *Lengths, areas, and volumes.* All of the units of the metric system are based upon natural standards. The meter was intended to be exactly 1/10,000,000 of the distance from the earth's equator to either pole. Because of a slight error, it equals that distance only approximately. By definition, the *standard meter* equals the distance, measured at 0° C., between two parallel lines scratched on a platinum-iridium bar kept at the International Bureau of Weights and Measures at Sèvres near Paris. From this standard, thousands of copies have been made. Our standard meter bar is kept at the Bureau of Standards in Washington, D.C. You will find the following table useful:

10 *milli*meters (mm.) make 1 *centi*meter
10 *centi*meters (cm.) make 1 *deci*meter
10 *deci*meters (dm.) make 1 meter (m.)

You will also need to know that there are 1000 meters in one *kilo*meter.

Since we have two systems, it is desirable to know the values of the metric units when compared to the English. *The meter equals 39.37 inches;* or, to put it the other way the yard equals $\frac{3600}{3937}$ of a meter. *One inch equals 2.54 cm.* One centimeter is approximately 0.4 of an inch. It is a small unit. (See Fig. 2–1.)

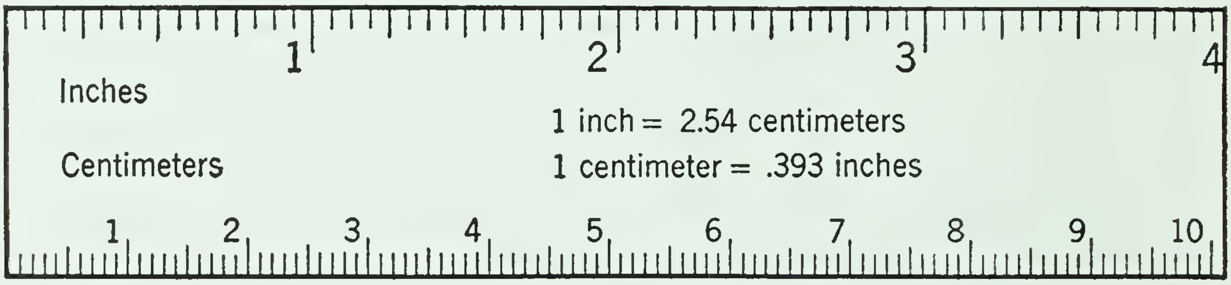


FIG. 2–1. The centimeter is nearly 0.4 of an inch in length. One inch equals 2.54 centimeters.

For measuring areas or surfaces, the *square meter* or the *square centimeter* is generally used. A floor 3 meters long and 2 meters wide has an area of 6 square meters. (See Fig. 2–2.) For measuring volumes, the *cubic meter* is used. A box 2 meters long, 1 meter wide, and 1.5 meters deep has a volume of 3 cubic meters. Vessels used for measuring liquids are often graduated in cubic centimeters (cc.). The abbreviation $\overline{\text{cm}}^3$. is frequently used instead of cc. Figure 2–3 shows the relative sizes of one cc. and one cu. in.

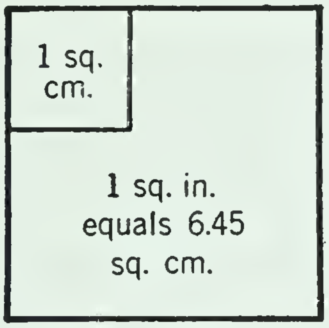


FIG. 2–2. Comparison of the metric and English units of area.

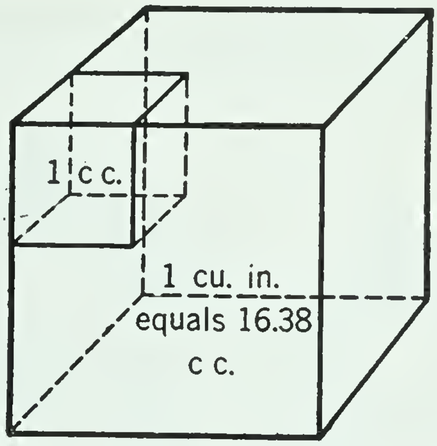


FIG. 2–3. The cubic inch contains more than 16 cubic centimeters.

Capacity. If we construct a cubical box whose inside dimensions are 10 cm. on each side, that box will hold exactly one *liter.* In the United States, we use a *dry* quart measure for measuring berries and vegetables, and a *liquid* quart for measuring milk or gasoline. The dry quart is about 10 cu. in. bigger than the liquid quart. The liter is used for measuring either liquids or solids; it is smaller than our dry quart, but a little larger than our liquid quart. (See Fig. 2–4.) *The liter is equivalent to 1000 cc., or to 1 cu. dm.* The same prefixes that are used in the table for lengths are used in the table for capacities in the metric system.

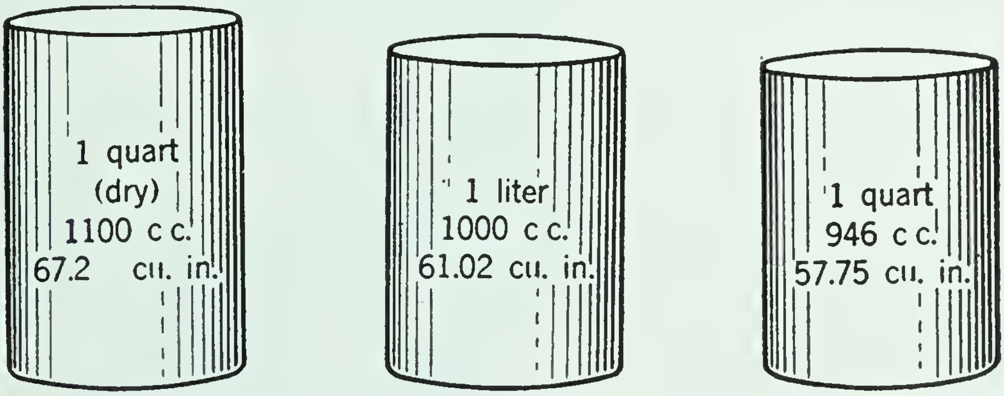

1 quart (dry) 1100 c c. 67.2 cu. in.
1 liter 1000 c c. 61.02 cu. in.
1 quart 946 c c. 57.75 cu. in.

FIG. 2–4. Our *dry* quart measure is larger than the liter, but our *liquid* quart is slightly smaller.

2. UNITS OF WEIGHT

For English and American units of weight, see Appendix A. Here we take up only the metric system of weights.

Water is used as a standard for weight. A cubical box whose dimensions are 10 cm. on each side will hold exactly *one kilogram* of distilled water measured at a temperature of 4° C. (4° Centigrade; equivalent to 39.2° Fahrenheit). From such knowledge we could construct a set of metric weights. One liter of water, or 1000 cc., weighs one kilogram. Therefore, *one cubic centimeter of water weighs one gram.* Both the gram and the kilogram may be used as standards of weight in the metric system. Here, too, in the table of weights the prefixes *milli*, *centi*, and *deci* are used. The metric ton (M.T.) is sometimes used; it is equal to 1000 kilograms.

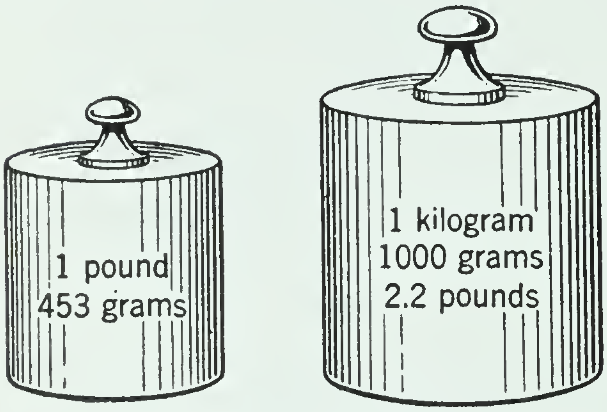
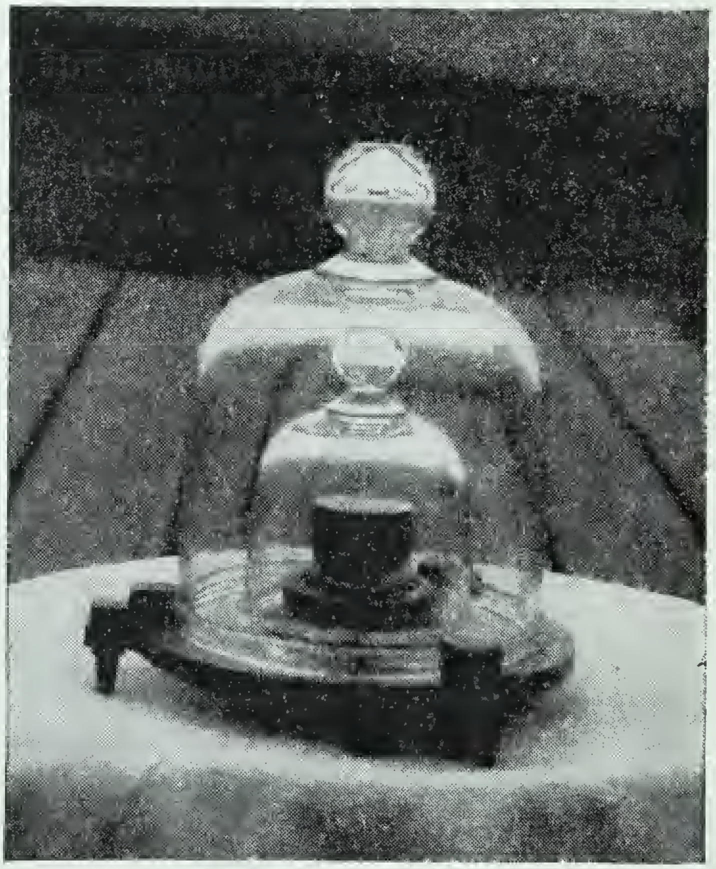


Fig. 2–5. The kilogram is more than twice as heavy as the avoirdupois pound.

The gram is a very small unit. A new five-cent piece weighs almost exactly 5 grams. The kilogram (kgm.) equals 2.204622 lb. Figure 2–5 shows the relative sizes of the pound weight and the kilogram weight.

The standard kilogram weight is a platinum-iridium cylinder kept with the standard meter at the International Bureau of Weights and Measures at Sèvres, France. A very accurate copy of this cylinder is kept in the National Bureau of Standards in Washington. (See Fig. 2–6.) In the



Courtesy of the National Bureau of Standards

Fig. 2–6. Our copy of the standard kilogram is carefully preserved.

United States the pound is defined legally as $\frac{1}{2.204622}$ of a kilogram.

3. UNITS OF TIME

How do we measure time? The metric system is often called the *centimeter-gram-second* (C.G.S.) system of measurement. The English system is known as the *foot-pound-second* (F.P.S.) system. In both English and metric systems of measurement, the *second* is the unit of time.

All civilized nations use the second, the minute, and the hour as units of time. One twenty-fourth of the day, from noon to noon, is the hour. The hour is divided into 60 equal parts, called minutes. A second is a sixtieth part of a minute. Thus a day contains 1440 minutes, or 86,400 seconds. Scientists use the second as the fundamental unit of time.

The most accurate clocks in the world are those at the United States Naval Observatory near Washington. These clocks are kept in an airtight vault in which a constant temperature is maintained. The passage of certain stars across the meridian is the means by which time is determined. This time is electrically transmitted to the clocks.

Demonstration. How do metric and English units of measurement compare? By comparing a meter stick and a yardstick determine the number of inches in a meter. Divide this number by the number of inches in a yard. By means of a balance weigh a one-pound weight in grams. By means of a spring balance weigh a kilogram weight in pounds. Compare all of the results with values given in Appendix A. Fill a quart container with water. By means of a graduated cylinder measure the water in cubic centimeters. How does a quart compare with a liter (1000 cc.)?

Demonstration. What is the difference between linear, area, and volume measurement? From a piece of cardboard, cut a section one foot square. Next construct a box, each side of which is one foot square. What is the linear measurement of the piece of cardboard? What is the area measurement of the box? What is the volume measurement of the box?

B. USE OF THE MICROMETER AND VERNIER CALIPERS

Precision measurements. It is often necessary to make linear measurements accurate to smaller fractions of a centimeter or an inch than is possible with an ordinary meter stick or yardstick. Such measurements are made with instruments constructed on the micrometer, or the vernier, principle.

The micrometer caliper. The micrometer caliper is used on many pieces of apparatus and on many machines for precision measurements. (See Fig. 2–7.) Its U-shaped frame is threaded so as to receive the spindle which forms the screw adjustment for the distance to be measured. (See Fig. 2–8.) The thimble is attached to the screw or spindle and has its beveled edge circumference divided into 100 equal parts. This constitutes the micrometer scale. The distance between adjacent threads of the screw is 1 mm. (this distance is called the pitch of the screw); therefore one revolution of the thimble opens or closes the caliper 1 mm. This causes the edge of the thimble to move 1 mm. to the right or left along the fixed horizontal index scale which is marked in centimeters and millimeters. One revolution of the thimble with its 100 divisions, therefore, divides the millimeter on the index scale into 100 equal parts. The screw

Photo by U. S. Army Signal Corps

FIG. 2–7. A defense worker using a micrometer caliper to check the accuracy of her work on a cannon-boring tool in a lathe.

is moved forward or backward 1/100 mm. or 1/1000 cm. when one division of the thimble is moved past the horizontal index line. The adjustment of the instrument must be such that when the jaws are together the zero line on the thimble scale exactly coincides with the horizontal index line at its vertical zero line.

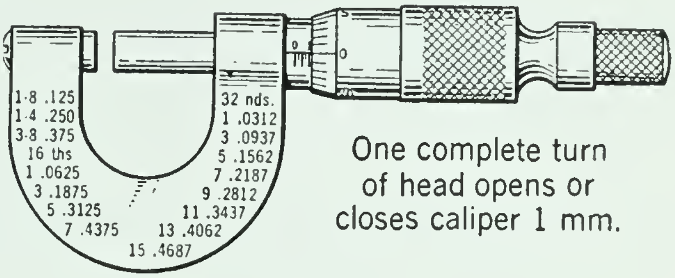


FIG. 2–8. The micrometer is used to measure to thousandths of a centimeter.

Some micrometer screws have a pitch of 0.5 mm. in order that two revolutions of the screw will be necessary to open or close the jaws a distance of 1 mm. In this case the beveled edge of the thimble is divided into 50 equal parts, thus making the instrument easier to read.

The vernier. The vernier, which was devised by a man of that name, consists of two scales; one is fixed, and the other is so arranged that it may slide along the fixed scale. Many instruments, such as the standard mercury barometer and the vernier caliper (see Fig. 2–9), use the vernier principle. This principle can be understood from a careful study of the vernier caliper. The fixed jaw of this instrument is attached to the left end of an arm on which slides the movable jaw. Both the metric scale and the English scale are ruled on the surface of the fixed arm. The vernier scale is ruled on the beveled edge of a flat surface which

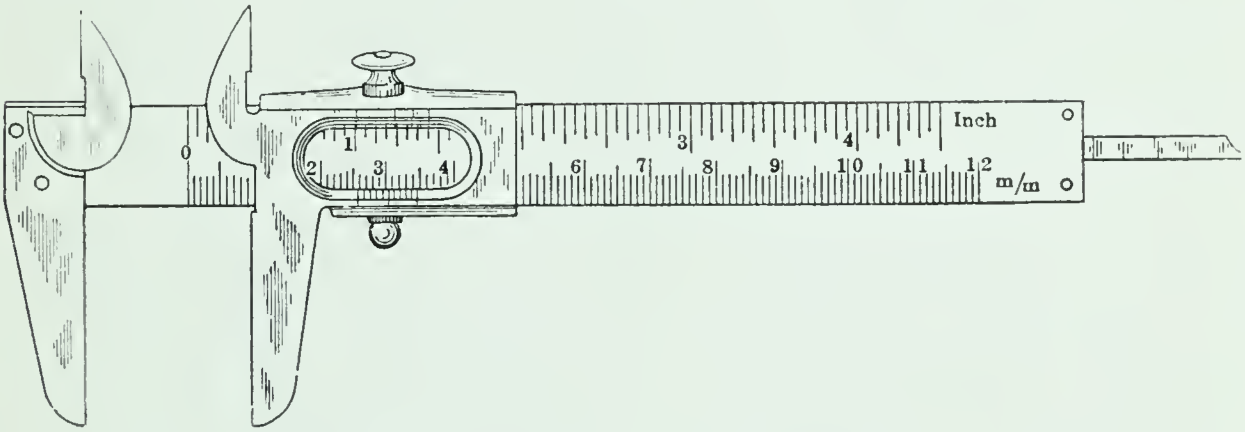


FIG. 2–9. The vernier caliper.

is a part of the jaw. When the jaws are closed it will be observed that the zero line on both linear and vernier scales coincides. The vernier (metric) scale's tenth line then coincides with the ninth line on the linear scale. (See Fig. 2–10.) One vernier unit, therefore, equals 0.9 of a scale unit or 0.9 mm. When the jaws of the vernier are in contact, the first mark of the vernier scale falls short of a mark on the fixed scale by 0.1 mm., and the second mark by 0.2 mm., and so on. Should the vernier be moved 0.1 mm. from its zero position, the first vernier mark on the sliding scale would coincide with the first mark on the fixed scale; should the vernier be moved 0.2 mm. from its zero position, the second vernier mark would coincide with the second mark on the fixed scale, and so on. The number of the line on the vernier scale which coincides with a line on the fixed scale represents the number of tenths of a millimeter or hundredths of a centimeter in the reading. A reading may be made on a vernier caliper as follows: note the left-hand division on the fixed scale nearest the vernier zero mark and express in tenths of a centimeter; then find the number of the vernier division which coincides with some fixed scale division; this number represents hundredths of a centimeter. For example, the reading shown by the dotted line position of the vernier in Figure 2–10 is 1.56 cm.

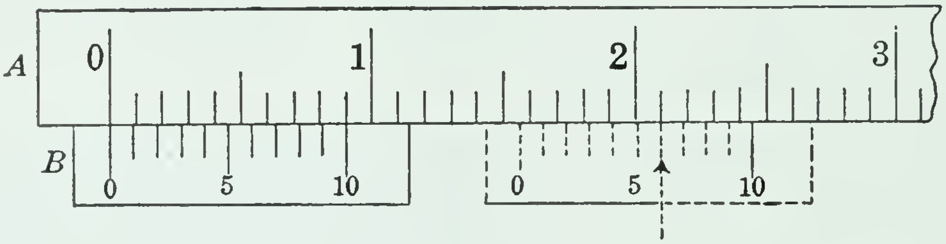


FIG. 2–10. Linear and vernier scales.

When a vernier is graduated in the English system, the fixed scale may be divided into inches and tenths, and the vernier made hundredths. Sometimes the fixed scale may be divided into inches and sixteenths, and the vernier made 128ths.

DEMONSTRATION. How are the micrometer caliper and the vernier caliper used in measuring? With which can greater accuracy be attained?

With a micrometer caliper measure the thickness of a page of this book. Next, measure the diameter of a strand of your own hair. With a vernier caliper measure the inside and outside diameters of a test tube.

C. DENSITY AND ITS DETERMINATION

1. DENSITY

The weight of a unit volume of a substance. Sometimes we hear it said that lead is heavy or that cork is light. Such a statement means little. A cubic *foot* of cork is heavier than a cubic *inch* of lead. Of course one cubic inch of lead is heavier than one cubic inch of cork. If we wish to be exact, we may say that lead is *denser* than cork. Suppose we have certain blocks containing exactly one cubic foot of each of the following: lead, iron, wood, cork, and less-known balsa. When each one is weighed, we find the weights of *equal volumes* decidedly different. (See Fig. 2–11.) *The weight of a unit volume of a substance is called its density.* Of course we could have found the weights of one cubic inch of each substance or of one cubic centimeter. The unit volume selected for use in the English system is *one cubic foot.* In the metric system it is *one cubic centimeter.* Hence, density is expressed in *lb. per cu. ft.*, or in *gm. per cc.*

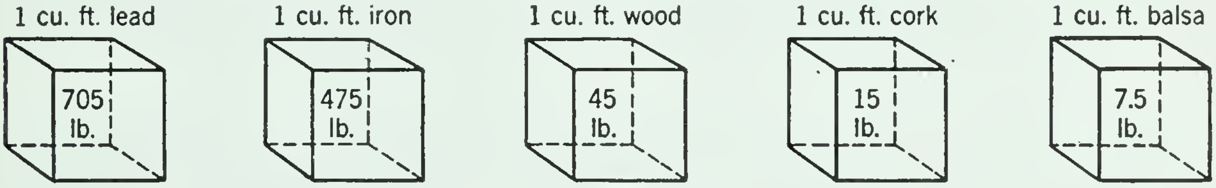


FIG. 2–11. Different substances have different densities, or different weights per unit volume.

To find the density of any substance we first weigh it. Then we find its volume, either by direct measurement or by the *indirect* method described on page 10. Next, we divide its weight by its volume to find the weight of unit volume.

Example. A block of wood weighs 180 gm. It is 10 cm. long, 6 cm. wide, and 4 cm. thick. Its volume is 240 cc. (10 cm. × 6 cm. × 4 cm.). If 240 cc. of wood weigh 180 gm., then 1 cc. weighs $\frac{180}{240}$ gm., or 0.75 gm. Therefore, the density of the block is 0.75 gm. per cc.

We may derive a formula for use in solving problems involving density. The letter D represents the density, the letter W represents the weight, and the letter V the volume. Then we have the following formula:

$$D = \frac{W}{V}, \text{ or } DV = W$$

$$\textit{Density} = \frac{\textit{weight}}{\textit{volume}} \text{ or } \textit{density} \times \textit{volume} = \textit{weight}$$

Many times we shall have occasion to make use of the density of water. *It has been found to be 62.4 lb. per cu. ft. in the English system*, sometimes written 62.4 lb./cu. ft. *In the metric system the density of water is one gram per cubic centimeter*, or 1 gm./cc. You should memorize these numbers.

PROBLEM. A gold brick is 15 cm. long, 10 cm. wide, and 5 cm. thick. If gold has a density of 19.3 gm./cc., calculate the weight of the brick.
Solution. The volume is equal to the product of the length, breadth, and thickness. In this case it is 750 cc. Since weight equals density times volume, then 750 × 19.3 gm. = 14,475 gm., the weight.

DEMONSTRATION. How can the density of a solid be determined by the direct-measurement method? Take a small, perfectly squared block of wood, and, with a vernier caliper, measure its width, thickness, and length, in centimeters. Determine the volume of the block by multiplying these three dimensions. Next, place the block on a balance and note its exact weight in grams. With the formula $D = \frac{W}{V}$ in mind, divide the weight of the block by its volume. The density of the wood per cc. is the result.

DEMONSTRATION. How can the density of an insoluble, nonporous solid be determined by the indirect method? Take a small stone of irregular shape which will go into a graduated cylinder of the type shown in Figure 1–2. Tie a fine thread about the stone and lower it into the cylinder. Cover the stone with water. Note the mark at which the water stands in the cylinder. Withdraw the stone and note the new mark at which the water stands in the cylinder. The difference between the two marks equals the volume of water displaced by the stone, and, consequently, the volume of the stone itself. Having determined the volume of the stone, find its weight, and finally its density as in the preceding demonstration.

2. DENSITY AND SPECIFIC WEIGHT

What are density and specific weight? Several times we have had occasion to mention the density of a substance. Sometimes it is an advantage to compare the density of one substance with that of another. For such a purpose, we need a standard. *Water is the standard* that physicists have chosen with which to compare the densities of all solids and liquids. For gases, *air* or *hydrogen* is used as the standard. In physics, we use the word *specific* to imply a ratio. Hence, *the weight of a substance compared to the weight of an equal volume of the standard*, such as water or air, *is called its specific weight.* Since we merely compare the density of a substance with the density of water, we might use the term *specific density.* The term *specific gravity* is often used, but those who are just beginning the study of physics seem to understand more easily the terms *specific weight* or *specific density.*

We find by experiment that 1 cc. of copper weighs 8.8 gm. We know from the definition that 1 cc. of water weighs 1 gm. In the metric system, the density of copper is 8.8 gm./cc. and the density of water is 1 gm./cc. Hence, copper is 8.8 times as dense as water. The *abstract number*, 8.8, which tells how many times as dense or "how many times as heavy" copper is as water, is called the specific density or the specific weight of copper. The density of copper is a *concrete* number, 8.8 gm./cc. The specific weight or *specific* density is an *abstract* number, 8.8. Numerically, they are the same in the metric system.

If we weigh 1 cu. ft. of copper, we find that it weighs 549.12 lb. One cu. ft. of water weighs 62.4 lb. By dividing 549.12 by 62.4 we get the abstract number 8.8. Of course the equal volumes of copper and water will have the same relative weights, whether they are both weighed in tons, pounds, ounces, or grams. In Appendix A you will find tables showing the specific weights of several substances. To find the density of any substance from the table, we *multiply 1 gm. by its specific weight* if we use the metric system, or *62.4 lb. by its specific weight* if we use the English system.

How do we find specific weight? We can find the specific weight of a substance experimentally by finding its density and dividing that number by the density of water. It is always true that:

$$\text{Specific weight} = \frac{\text{density of } x \text{ substance}}{\text{density of water}}$$

Possibly it is easier to use a slightly different statement and then proceed to explain how each term can be found experimentally:

$$\text{Specific weight} = \frac{\text{weight of } x \text{ substance}}{\text{weight of same volume of water}}$$

We can easily find the *weight of the same volume of water*, since a body submerged in water loses as much weight as the weight of the water displaced. In general, then, we proceed as follows when we wish to find the specific weight of any body: (1) we weigh the body to find its weight in air; (2) we find the weight of an equal volume of water by finding how much weight the body loses when submerged in water; (3) we divide the weight of the body by the weight of the same volume of water.

How do we find the specific weight of solids? (1) *Solids heavier than water.* If the solid is insoluble, we first weigh it in air and then weigh it in water. The *difference* between the two weights is the loss of weight in water, or the weight of the same volume of water.

$$\text{Specific weight} = \frac{\text{weight in air}}{\text{loss of weight in water}}$$

PROBLEM. A stone weighs 30 gm. in air, and 20 gm. in water. Find its specific weight.

Solution. Loss of weight in water is 10 gm. Then, 30 gm. ÷ 10 gm. = 3, the sp. wt. The volume of the stone must have been 10 cc., since 1 cc. of water weighs 1 gm.

(2) *Solids lighter than water.* Since a floating object loses all its weight in water, or seems to, it is more difficult than with heavy solids to find its volume, or "the weight of the same volume of water." It is possible to use a sinker. If we find the buoyant effect on the *sinker alone,* and then the buoyant effect upon the

light solid with sinker attached, the difference is the buoyant effect on the *light solid alone.* (See Fig. 2–12.) We proceed as follows:

(*a*) We weigh the solid in air and call its weight w.

(*b*) We find combined weight, solid in air and sinker in water, calling the sum w'.

(*c*) We then find the combined weight of both in water, calling this weight w''.

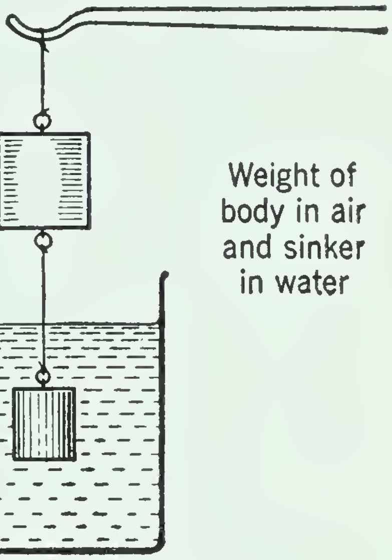


FIG. 2–12. Specific weight of bodies lighter than water.

The difference between w' and w'' is equal to the buoyant force on the solid alone, or the weight of an equal volume of water. Hence the formula:

$$\text{Specific weight} = \frac{w}{w' - w''}$$

$$\frac{\textbf{weight of solid in air}}{\textbf{combined weight of solid in air and sinker in water} - \textbf{combined weight of both in water}}$$

PROBLEM. A piece of cork weighs 50 gm. A sinker immersed in water weighs 210 gm. The combined weight of the cork and sinker when submerged is 10 gm. Find the sp. wt. of the cork.

Solution. Specific weight $= \dfrac{w}{w' - w''}$. The weight of an equal volume of water is found by subtracting 10, the weight of both when submerged, from 260, the combined weight of cork in air and sinker in water. Then $50 \div 250 = 0.2$, sp. wt. of cork.

How do we find the specific weight of liquids? There are several methods for comparing the weight of a liquid with that of an equal volume of water. A few are given here.

(1) *The bottle method.* A small flask or bottle, like that shown in Figure 2–13, is first weighed. Then it is filled with water and again weighed. Next it is filled with the liquid of x specific weight and weighed a third time. By subtracting the weight of the empty

bottle from each of the latter weighings, we find the weight of water that the bottle can hold and the weight of the liquid of unknown specific weight that it can hold.

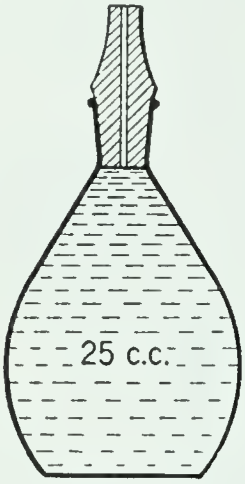


FIG. 2–13. A pycnometer can be filled with great precision.

$$\text{Specific weight} = \frac{\text{weight of } x \text{ liquid}}{\text{weight of water}}$$

The bottle shown in the figure is called a *pycnometer.* Since its stopper is made of ground glass, it fits perfectly. The tiny hole through the stopper makes it easy to fill the pycnometer with exactly the same volume of liquid each time.

EXAMPLE. A small bottle weighs 22 gm.; filled with water it weighs 72 gm.; filled with alcohol it weighs 62 gm. Find the specific weight of the alcohol.

Solution. The bottle holds 50 gm. of water. It holds 40 gm. of alcohol. The specific weight of alcohol equals $\frac{40}{50}$, or 0.8.

(2) *Loss-of-weight method* or *bulb method.* Pieces of cork and sticks of wood float on water. If the lungs are filled with air, the human body floats on water. Such facts furnish evidence that water exerts an upward pressure, or *buoyant force,* upon objects immersed in it. An object will float if the buoyant force of the water which it displaces is equal to the weight of the object itself. Objects denser than water, even though they sink readily, appear to lose a part of their weight when submerged. For example, a man can lift a larger stone under water than he can possibly lift in air, because the buoyant force of the water lifts part of the weight. *The upward force which any liquid exerts upon a body submerged in it is called its buoyancy.*

The denser a liquid, the greater its buoyancy. Hence we can find the relative weights of two liquids by comparing their buoyant effects upon some solid. A glass bulb or a platinum ball is most often used. First *we weigh the bulb in air, then in water, and then in the liquid of x specific weight.* Of course the bulb will displace the same volume of each liquid. If it loses twice as much weight in the x liquid as in water, then the x liquid must be twice as dense as water. In general, the following formula is true:

$$\text{Specific weight} = \frac{\text{loss of weight in } x \text{ liquid}}{\text{loss of weight in water}}$$

EXAMPLE. A ball weighs 40 gm. in air, 32 gm. in water, and 28 gm. in a liquid of unknown density. Find the specific weight of the liquid.

Solution. Loss of weight in x liquid is 12 gm.; the loss of weight in water is 8 gm. The buoyancy of the x liquid compared with the buoyancy of water is $\frac{12}{8}$ or 1.5. Therefore the specific weight of the liquid is 1.5.

(3) *The hydrometer method.* A wooden rod, loaded at one end so that it will float vertically, sinks in water until the weight of the water it displaces exactly equals its own weight. Placed in a liquid of unknown specific weight it sinks until the weight of x liquid displaced equals its own weight. If the rod is uniform, the relative volumes of liquids displaced will be proportional to the depths to which the rod sinks. For example, if the rod sinks 10 cm. in water, and to a depth of 8 cm. in x liquid, then x liquid is $\frac{10}{8}$, or 1.25 times as dense as water.

$$\text{Specific weight} = \frac{\text{depth rod sinks in water}}{\text{depth rod sinks in } x \text{ liquid}}$$

The *commercial hydrometer* has a scale so graduated that the specific weight of the liquid in which it floats may be read directly. (See Fig. 2–14.) The upper bulb is designed to increase the volume of the hydrometer, while the lower bulb is filled with shot or mercury so that the vertical position of the hydrometer will be maintained as it floats. Hydrometers may be made for use with liquids less dense than water, or for those more dense than water. It is possible to have a hydrometer for use with either type of liquid.

Knowing specific weight is important. We use specific weight to help us identify rocks and minerals. Naturally, too, men are interested in alloys that are light, yet strong for use in airplane parts. We may use specific weight in helping to judge the purity of substances, particularly liquids. For example, we have special hydrometers that are used to tell us when our storage battery needs recharging. A fully charged battery has a higher specific weight than one that has lost most of its charge. Some special hydrometers called *acidimeters* find use in testing the *concentration* of acids. The *alcoholometer* is a special hydrometer for measuring the per cent of alcohol in a mixture of alcohol and water. A special hydrometer called a *lactometer* is used to indicate whether water has been added to milk. Milk is slightly more dense than water, having a specific weight of about 1.029. A filling-station attendant estimates the freezing point of the mixture of alcohol and water in your automobile radiator by using a special hydrometer to check the specific weight of the antifreeze mixture. A low density indicates a low freezing point.

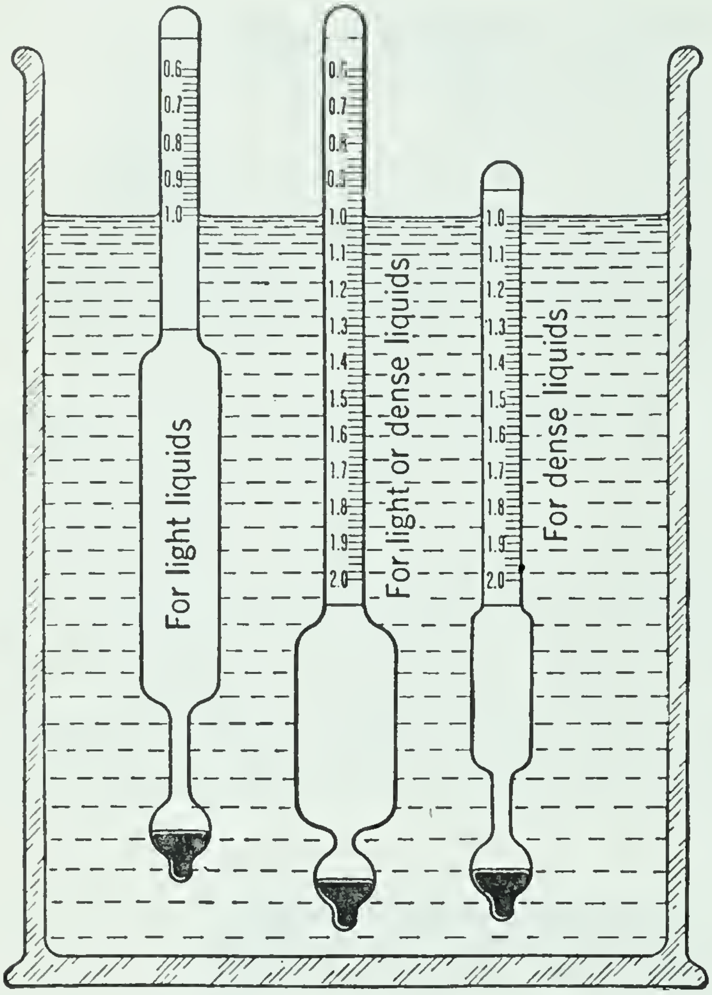


FIG. 2–14. Hydrometers of different types.

SUMMARY

1. You should memorize the following metric-English equivalents: 1 m. equals 39.37 in.; 1 in. equals 2.54 cm.; 1 kgm. equals 2.2 lb. Other equivalents are given in Appendix A.

2. The density of a substance is the weight of a unit volume of that substance. You should remember that 1 cc. of water weighs 1 gm.; also that 1 cu. ft. of water weighs 62.4 lb. For solving problems, the following formula is useful:

$$\mathbf{D = \frac{W}{V}} \qquad \left(\textbf{Density} = \frac{\textbf{weight}}{\textbf{volume}}\right)$$

3. In the United States the pound is defined in terms of the standard kilogram.

4. Density is the weight per unit volume. Specific weight is the weight of a certain volume of substance divided by the weight of the same volume of water.

5. Specific weight is found by dividing the weight of a body by the weight of a volume of water exactly equal to the volume of the body. The latter is numerically equal to the loss of weight of the body in water.

6. The upward force a fluid exerts on a submerged body is called its buoyancy.

7. The buoyancy of a liquid varies directly with its density.

How many of the following terms can you define or explain?

Metric system
Meter
Centimeter
Cubic centimeter
Liter
Gram
Kilogram
C.G.S. system
F.P.S. system
Micrometer
Vernier
Density
Specific weight
Hydrometer

SELF-TESTING EXERCISES

Answer These Questions

On a separate sheet of paper numbered from 1 to 7 write the letters for the phrases that answer the following questions correctly.

1. Which of these statements is true about the metric system? (*a*) It is used only in the United States and England; (*b*) it is a decimal system; (*c*) it is the F.P.S. system.

2. $\frac{1}{1440}$ of a day is what? (*a*) second; (*b*) minute; (*c*) hour.

3. Which substance is used as the standard for weight? (*a*) gold; (*b*) water; (*c*) platinum; (*d*) iron.

4. Weight per unit volume of a substance is known as (*a*) mass; (*b*) specific weight; (*c*) density.

5. Aluminum weighs 2.7 times as much as an equal volume of water. What does the abstract number 2.7 mean in this case? (*a*) weight; (*b*) density; (*c*) mass; (*d*) specific weight.

6. What do we call the upward force which a liquid exerts upon a body

submerged or floating? (*a*) tension; (*b*) specific gravity; (*c*) buoyancy; (*d*) friction.

7. The hydrometer is an instrument for measuring what? (*a*) volume of liquids; (*b*) specific weight of liquids; (*c*) density of liquids.

COMPLETE THESE STATEMENTS

On a separate sheet of paper numbered from 1 to 7 write the words needed to fill correctly the blank spaces in the following sentences.

In both English and metric systems the ..(1).. is the unit of time. At 4° C. a cubic centimeter of water weighs ..(2)... Shorter distances can be measured by the ..(3).. caliper than by the ..(4).. caliper. In the United States the pound is defined legally in terms of the metric unit, the ..(5)... In the metric system the density of a solid or liquid is numerically the same as its ..(6)... We may use ..(7).. in helping to judge the purity of a substance.

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 7 write a T *or an* F *to show whether each statement is true or false.*

1. The meter is about $\frac{1}{1\,000,000}$ of the distance from the earth's equator to either pole.
2. One kilogram equals approximately 2.2 lb.
3. One liter is equivalent to one pint.
4. Specific weight for a given substance is not the same numerically in the metric and English systems.
5. The more dense a liquid, the greater will be its buoyant effect upon a submerged object.
6. A form of hydrometer is the lactometer.
7. Air is used as a standard for measuring density of gases.

QUESTIONS

1. What advantages has the metric system of weights and measures over the English system?
2. Why is it more exact to say that lead is "dense" than to say that lead is "heavy"?
3. Why is water used as the standard for both weight and specific weight?
4. Some hydrometers are made for use with liquids lighter than water. Would you expect the upper bulb on such a hydrometer to be relatively large or rather small? Explain.
5. What is the purpose of the lower bulb of a hydrometer?

6. Some hydrometers are made for use with liquids denser than water. What would you suggest concerning their construction?

7. Some hydrometers are made for use either in light liquids or in heavy liquids. Make a sketch to show how they are constructed and graduated.

8. Denatured alcohol mixed with water is used in automobile radiators in winter. The larger the per cent of alcohol, the lower the freezing point of the mixture. How can a hydrometer be used to test the freezing point of such a mixture?

9. Suppose that you were handed a crown and asked to find out whether it was made of pure gold. Without destroying the crown, just how would you proceed?

10. Which do you think will have the higher specific weight, whole milk or skim milk? Give a reason for your answer.

11. Which has the higher specific weight, a heavy cream or a light cream? Explain.

12. Milk from the Jersey breed of cows has a higher per cent of butter fat than milk from some other breeds. How would you expect the lactometer reading to be affected by the high per cent of fat?

13. Why are density and specific weight the same numerically in the metric system?

14. Why are density and specific weight different numerically in the English system?

15. Make a list of as many uses as you can for the hydrometer.

PROBLEMS

(*Refer to Tables 1, 2, 3, and 4 in Appendix A.*)

1. Calculate the value of 1 ft. in cm.; of 1 oz. in gm.

2. Calculate your height in meters; your weight in kilograms.

3. The Empire State Building is 1248 ft. high. What is its height in meters?

4. A train runs the 960 miles from New York to Chicago in 18 hours. What is its average speed in miles per hour?

5. A train runs at the speed of 100 kilometers per hour. What is its speed in meters per second?

6. With its approaches, the San Francisco-Oakland Bridge is 8.5 miles long. What is its length in kilometers?

7. A tank is 6 ft. long, 4 ft. wide, and 5 ft. deep. How many pounds of water can it hold?

8. Stone has a density of 150 lb. per cu. ft. Calculate the weight of one cubic yard of stone.

9. A manufacturer wishes to make a 1000-gm. brass weight. How many cc. of brass, density 8.4 gm. per cc., will be needed?

10. Calculate the number of grams in one ounce. How many centimeters are there in one yard? How many kilometers are there in one mile?

11. A block of iron weighs 50 gm. in air, and 43.5 gm. in water. Find its sp. wt.

12. A block of aluminum weighs 50 gm. in air, and 31.5 gm. in water. Calculate the sp. wt. of aluminum.

13. Explain why 50 gm. of aluminum lose nearly 3 times as much weight in water as 50 gm. of iron.

14. What is the meaning of the expression, "The specific weight of tungsten is 18.7"? What will 10 cc. of tungsten weigh in air? What will be the weight of 10 cc. of tungsten in water? What will 10 cc. of tungsten weigh in gasoline, sp. wt. = 0.7?

15. What will be the weight of 1 cu. ft. of tungsten?

16. How much weight will 50 cc. of platinum lose in water? How much weight will 50 cc. of magnesium lose in water?

17. How much weight will 50 gm. of platinum lose in water? How much weight will 50 gm. of magnesium lose in water?

18. A body weighs 500 lb. in air and 400 lb. in water. Find its sp. wt. Calculate its volume. What is its density?

19. A small flask weighs 35 gm. Filled with water, it weighs 135 gm. Filled with salt water it weighs 150 gm. It weighs 105 gm. when filled with gasoline. Calculate: (*a*) sp. wt. of the salt water; (*b*) sp. wt. of the gasoline.

20. A flask weighs 30 gm. Filled with water, it weighs 55 gm.; filled with chloroform, it weighs 67.5 gm.; and filled with glycerine, it weighs 61.5 gm. Find (*a*) the volume of the flask; (*b*) the sp. wt. of chloroform; (*c*) the sp. wt. of glycerine.

21. A glass bulb weighs 60 gm. in air, 30 gm. in water, and 18 gm. in nitric acid. Find (*a*) the volume of the bulb; (*b*) the sp. wt. of the bulb; and, (*c*) the sp. wt. of nitric acid.

III

Theory of Machines

A. WHY DO WE USE MACHINES?

1. TO DO WORK

How does a machine do work? We have already seen that machines have enabled man to use his own strength more efficiently, and also to use other forces. All machines are used to help do some kind of work for man. Without the aid of machines, man could hardly have been able to combat the tremendous forces of nature or conquer the ferocious beasts of our forests. Perhaps in many cases necessity was the mother of invention. The Greek scientist Archimedes said that he could lift the earth if he had a long enough lever and some place to put the fulcrum. Man uses some machines to *transform energy*. The dynamo, for example, changes mechanical energy into electrical energy. The steam engine transforms heat energy into mechanical energy. The energy of flowing water is transformed into electrical energy by hydroelectric machines. Man often uses machines to *transfer energy* from one place to another. A machine, then, does work by *transforming* or *transferring energy.*

2. TO ENABLE US TO UTILIZE ENERGY EFFICIENTLY

To put up a flag on a tall pole, one *could* climb the pole and carry the flag with him. It is much more convenient, however, to have a pulley at the top of the pole, and a rope twice the length of the pole. Then one can stand on the ground and pull the flag up by means of the rope. He must pull downward with a force of 1 lb. for every pound the flag weighs. Hence this single pulley as a machine *does not multiply force.* He must shorten the rope one foot for every foot the flag is raised; hence the pulley *does not multiply speed.* Such a machine is used only as a convenience *to* *change direction.* The pulley clothesline, the pulley for lifting awnings, and many similar devices, are other examples of machines used to change direction. The farmer who wishes to use a team of horses to lift hay up into a mow would have difficulty in getting his horses up into the mow to pull upward. He would find it difficult to hitch his horses to a rope so that they could pull downward. By the use of two or three fixed pulleys, fastened to the rafters and along the post by the side of the barn door, the horses can pull horizontally and move the hay upward.

3. TO MULTIPLY FORCE OR SPEED

A nail that cannot be pulled with the fingers may be drawn with a claw hammer used as a lever. By means of a jack, the axle of an automobile can be lifted so that the wheel or tire can be removed. Two men want to hoist a piano to the second floor of a house. If either one were strong enough, he might carry it upstairs. Instead they arrange a system of pulleys called a *block and tackle* by means of which the piano can be hoisted with less force. In all these cases, a machine has been used to multiply man's rather feeble force. *One important use of machines is to multiply force or effort.* Since in every case the time has been increased, *we gain effort at the sacrifice of time or speed.*

A bicycle is a machine used *to gain speed.* In this case we gain speed by increasing our effort. If we try to ride a bicycle uphill we become aware of the fact that we are gaining speed by increased effort. It is impossible to gain both force and speed at the same time. The bones of the forearm are levers used to gain speed. We see that *machines are used by man to multiply speed.*

B. ENERGY

1. THE CAPACITY TO DO WORK

How are matter and energy related? We did not include heat, light, and electricity among the examples of matter. They do not take up room, and we should find it difficult to weigh them.

They are really forms of energy. *One usually defines energy as the capacity to do work.* Man puts heat energy to work in a steam engine. In many cases we call upon electrical energy to do our work for us. The photographer uses light energy when he exposes a film or plate.

Flowing water has energy because the pull of gravity has given it velocity. Wind is a similar example. Waves and tides, too, have energy. An inanimate body has energy, provided work has been done in lifting it to an elevated position or in imparting to it velocity. In the first case it has energy of position. In the second case it has energy due to its motion.

It takes energy to move a body. We must heat a piece of wood to make it burn, but it gives out heat as it burns. We use heat energy to start the fire, but when once started the fire gives out heat energy. In order to bring about any change in the condition or state of matter, energy must be used. In turn, changes in matter itself may liberate some form of energy.

What are some kinds of energy? Several kinds of energy are known: *mechanical energy*, which may be produced by some kind of machine; *heat energy*, *electrical energy*, *light energy*, and *chemical energy.* For doing chemical work all the above-named kinds of energy are in use.

It is possible to *convert* or to *transform* one kind of energy into another form of energy. For example, one may use heat energy from burning coal to form steam; the steam may be used in a steam engine to produce mechanical energy; such energy may be used to run a dynamo to generate electricity; the electrical energy from the dynamo may in turn be converted into heat energy, into light energy, or into the mechanical energy needed to drive an electric motor.

2. KINETIC AND POTENTIAL ENERGY

Energy of motion and energy of position. It is possible to have *energy in motion* and *energy at rest.* *Kinetic energy is energy of motion;* a body has kinetic energy because of its velocity. A moving cannon ball, strong winds, falling and running water are all examples of kinetic energy. *Potential energy is stored energy,* or *energy of position.* A rock resting on a precipice has potential energy; if it falls over the edge, its energy becomes kinetic. A coiled spring has potential energy. Work was done in winding the spring; as it unwinds, its energy becomes kinetic. Gasoline has potential energy. When a mixture of gasoline vapor and air explodes, it is capable of doing work. If we pull to one side a heavy pendulum bob, we are storing up *potential* energy as we lift the bob against gravity. As the bob swings downward and forward, the potential energy becomes *kinetic.* The kinetic energy released is sufficient to carry the bob upward again on the opposite side, thus storing up more potential energy. It is possible to change kinetic energy to potential, and vice versa.

3. ENERGY IS MEASURED IN FOOT-POUNDS AND GRAM-CENTIMETERS

To measure energy we must consider two factors: the force exerted, measured in pounds or grams; and the distance, measured in feet or centimeters, through which the force is moved. If a book weighs one pound it is necessary to exert a force of one pound to lift it. To lift the book one foot would require one English unit of energy, one *foot-pound* (ft.-lb.). Similarly, a gram of force moved one centimeter would represent the metric unit of energy, the *gram-centimeter* (gm.-cm.).

We expend 120 ft.-lb. of energy in lifting a 40-lb. weight to a table 3 ft. high. (See Fig. 3–1.)

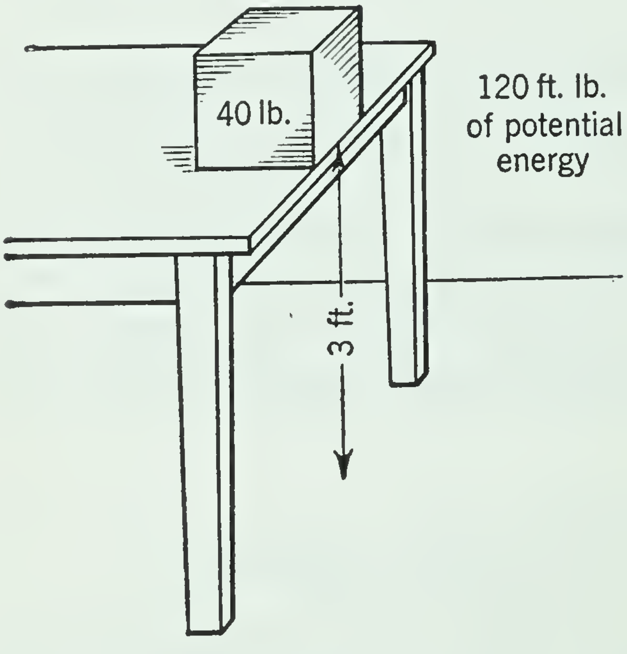


Fig. 3–1. Potential energy equals weight times vertical height. As the weight falls, its energy becomes kinetic.

Energy = weight × distance

The 40-lb. weight in its elevated position has acquired 120 ft.-lb. of potential energy. In falling a distance of 3 ft., this stored energy would become 120 ft.-lb. of kinetic energy.

Demonstration. What relation is there between the kinetic energy and potential energy of a body? Weigh a metal sphere, or some other dense material. From a height of one meter allow the ball to fall upon a board on the table. Examine the damage done to the board. How much work was done in lifting the sphere to a height of 100 cm.? How much work (gm.-cm.) was done on the board? What two kinds of energy have been involved?

Potential energy therefore equals mh, or mass times height. If the mass is expressed in grams and the height or distance in centimeters, then the potential energy will be expressed in gram-centimeters. If the mass is expressed in pounds and the distance in feet, the potential energy will be expressed in foot-pounds.

4. LAW OF CONSERVATION OF ENERGY

Like matter itself, energy can be neither created nor destroyed. There is the same amount of energy in the universe today that there was yesterday, and the amount will be unchanged tomorrow. These facts show why the *output* of a machine can never exceed the *input.* A perpetual-motion machine is utterly impossible. Even if friction and the weight of the parts could be eliminated, the machine could never create energy; it would never have any more energy than was put into it.

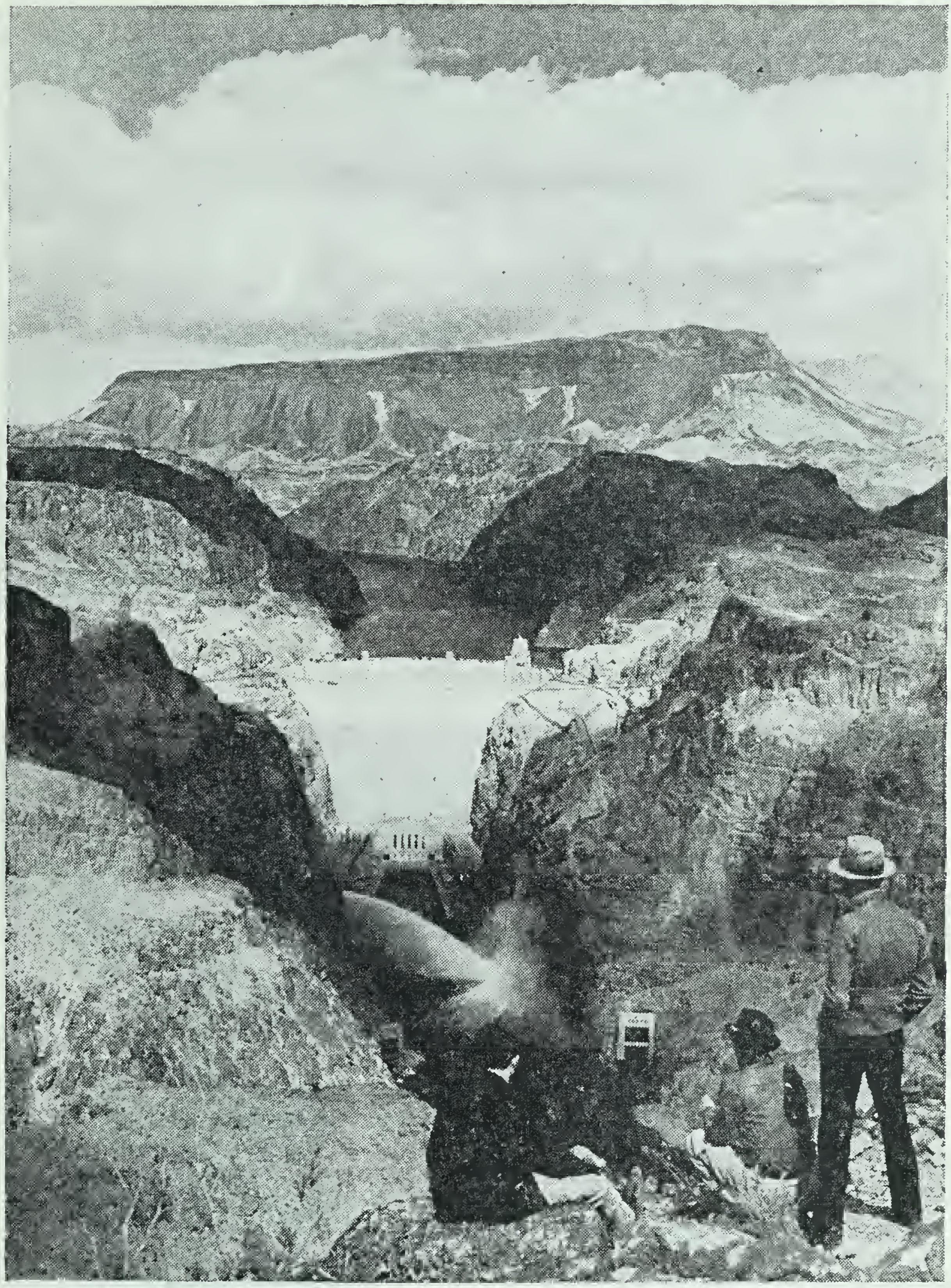
In the earth's treasure house we find energy stored in coal and petroleum. It is not doing any work so long as it is *stored* energy, but it is capable of doing work when it is changed into kinetic energy. When gasoline, which is obtained from petroleum, explodes inside the cylinder of a gasoline engine, its potential energy is changed to kinetic energy in the running of the engine. The sugar which you eat with your oatmeal has potential energy. How may it become kinetic energy?

Although energy cannot be created, it can be transformed from one kind into another. We have already learned that it is possible to transform kinetic energy into potential energy, and vice versa. Heat energy can be transformed into mechanical energy, mechanical into electrical, and electrical into mechanical, heat, or light energy. Let us use just one concrete example. Heat from the sun evaporates water; some of this vapor, which is carried by winds, may fall as rain into Lake Erie. Here its potential energy is transformed into kinetic as the water flows down Niagara River to the Falls. This transformation continues as it passes through the turbine pits and turns the large wheels at the bottom, thus producing mechanical energy. The turbines turn alternators which generate electricity. This electrical energy is transmitted to various places, where it is utilized for lighting, heating, or in the mechanical work of turning motors. In these cases heat energy is set free, either in doing useful work or in overcoming friction. This heat may evaporate more water to begin anew the energy transformations. During all these transformations the total amount of energy is unchanged. The fact that energy may be transformed or transferred, but cannot be destroyed, is known as the *law of conservation of energy.* Huge Boulder Dam stores up tremendous potential energy. Already a powerhouse which can develop 1,835,000 horsepower has been put into operation. (See Figs. 3–2 and 3–3.)

C. FORCE

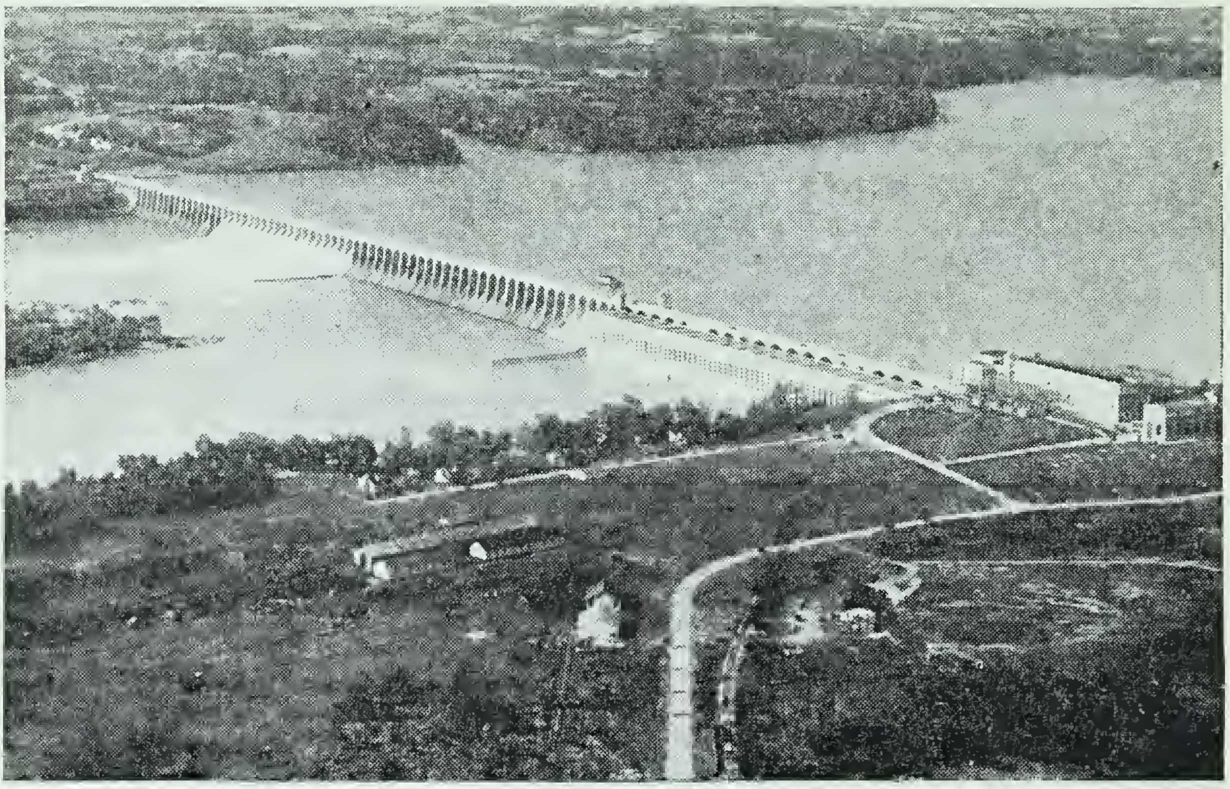
1. FORCE IS A PUSH OR A PULL

Force tends to, or actually does, produce or prevent motion. The term "force" is not entirely new to us, but perhaps we need to discuss it more fully. It has been defined as a "push" or a "pull"; it may also be defined as muscular exertion or its equivalent. If we pull upon a locomotive, we may move it or we may merely *tend* to move it. In either case we are using force. A truck starts downhill; if we push backward against it we may stop it, or we



Courtesy of the Department of the Interior

Fig. 3–2. Boulder Dam, built in Black Canyon, impounds water for irrigation purposes and for furnishing some 1,835,000 horsepower of electrical energy. The dam is 726 ft. high and the length of its crest is 1200 ft. The base of the dam is 650 ft. thick. It is the highest dam in the world, and it took nearly five years to complete the work. The thickness at the top is 45 ft. A total of 4,360,000 cu. yd. of concrete was used in its construction.



Courtesy of T.V.A.

FIG. 3-3. Wilson Dam is another source of great power.

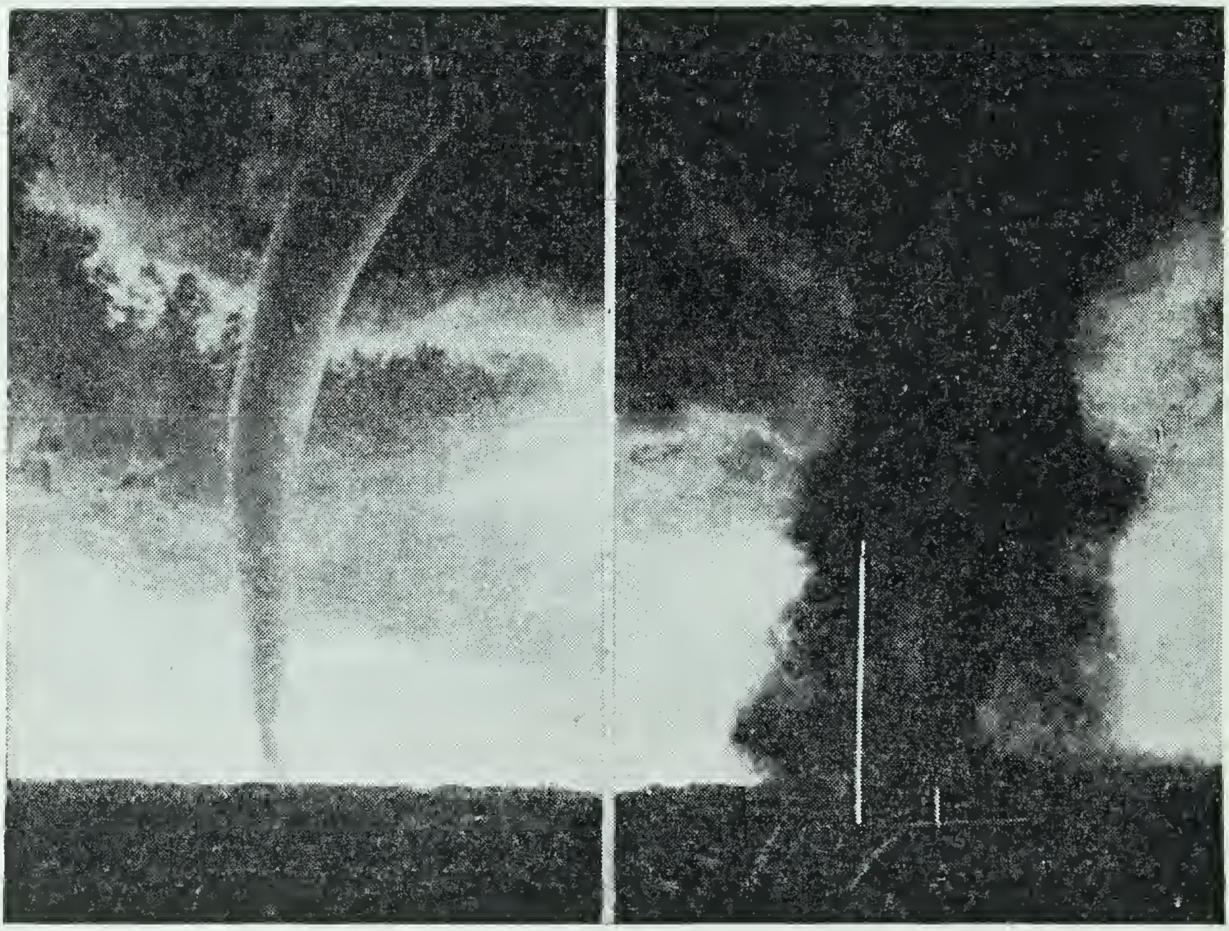


FIG. 3-4. When the velocity of the wind in a tornado reaches from 100 to 200 miles per hour, it destroys practically everything in its path.

may merely *tend* to stop it. We are using force in either case. Some forces are tiny ones, while others are stupendous. *Forces produce or prevent motion, or they have a tendency to do so.* Man sometimes uses the force of the wind, the waves, and the tides for his own purposes. Sometimes he uses other forces to try to counteract the destructive forces of these agents. (See Fig. 3–4.)

2. FORCE IS MEASURED IN POUNDS AND GRAMS

How is force measured? The spring balance is one of the common means of measuring force. The pull of the earth upon *one gram of mass* suspended from the hook of the balance will stretch the spring a certain distance. Two grams of mass will stretch the spring twice as far, and so on. The graduations are marked upon the face of the balance, which is independent of the spring. A pointer attached to the spring indicates the reading. (See Fig. 3–5.) In the use of the beam balance for measuring forces, the pull of the earth upon the object placed upon one beam of the balance is counterpoised by weights of known magnitude placed upon the other beam. Some balances of this type are exceedingly sensitive. (See Fig. 3–6.) In assaying gold ores it is necessary to use very sensitive balances. In the chemical laboratory, microbalances are used to weigh minute quantities of material. Much attention is given to microanalysis, in which the chemist must determine the amount of poison or other chemical, even when present only in tiny grains or crystals.

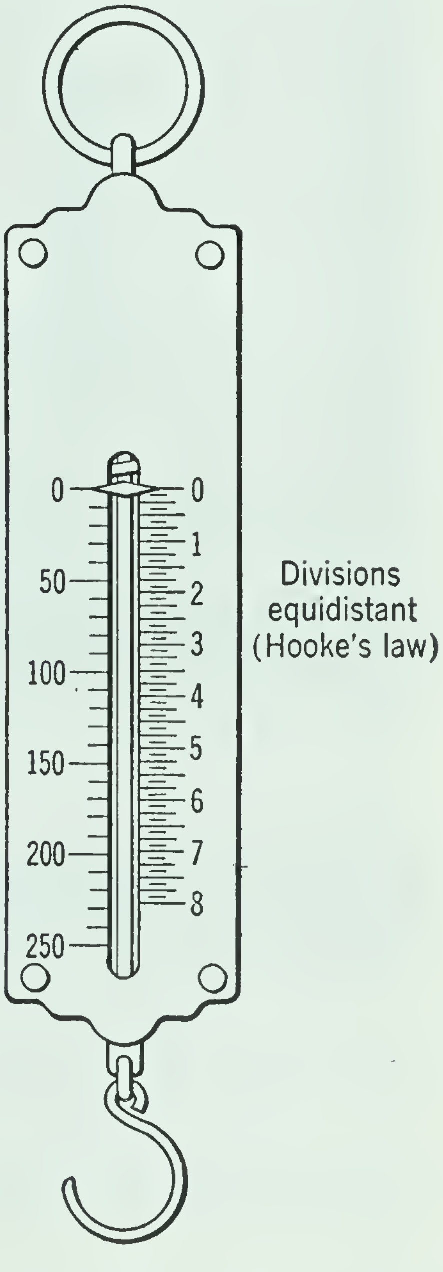
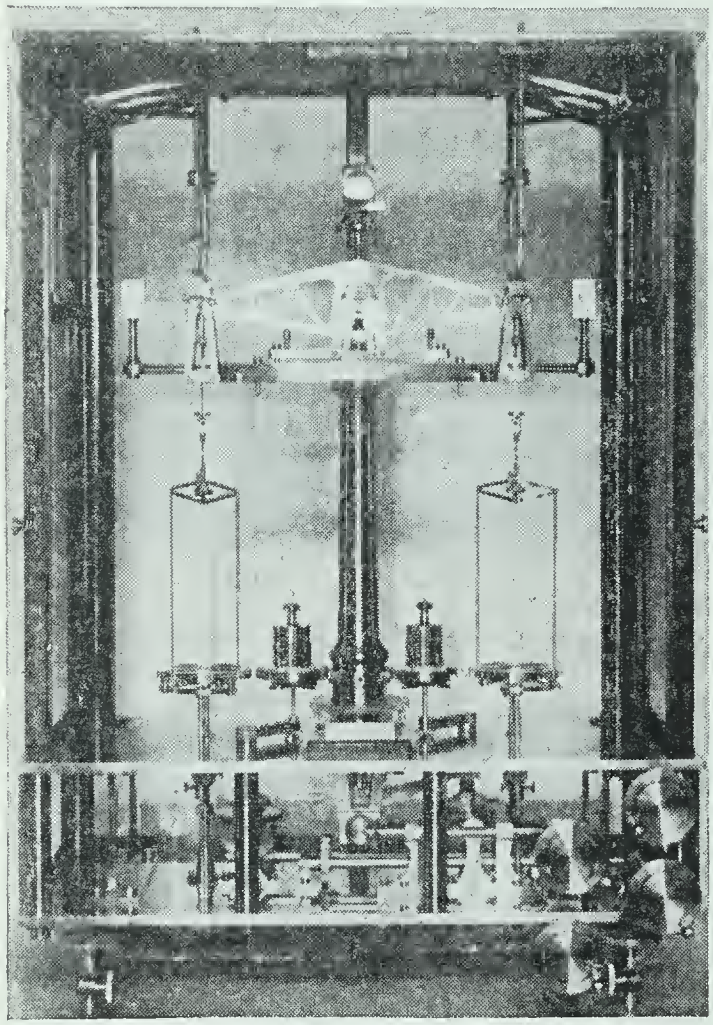


FIG. 3–5. The spring balance may be used to measure force.

What are the units of force? To measure forces, or to compare them, some definite units must be used. In all our work, we have used the *gram of force* and the *pound of force*. They are called the *gravitational units*, since they are based upon the earth's attraction. For example, a gram of force is the pull which the earth exerts upon one gram of mass, and the pound of force is the pull which the earth exerts upon one pound of mass. But the earth's pull upon one gram of mass is greater at the poles than it is at the equator; it is more in a valley than upon a mountaintop. For the same reason that weight, or the measure of the earth's attraction, varies, these units also vary. At the latitude of New York, *a gram of force acting continuously for one second upon a gram of mass imparts to it a velocity of approximately 980 cm. per second.* At the equator this velocity is only about 978 cm. per second, but at the North Pole it is about 983 cm. per second. *A pound of force acting for one second upon a mass of one pound imparts to it a velocity of 32.16 ft. per second.*



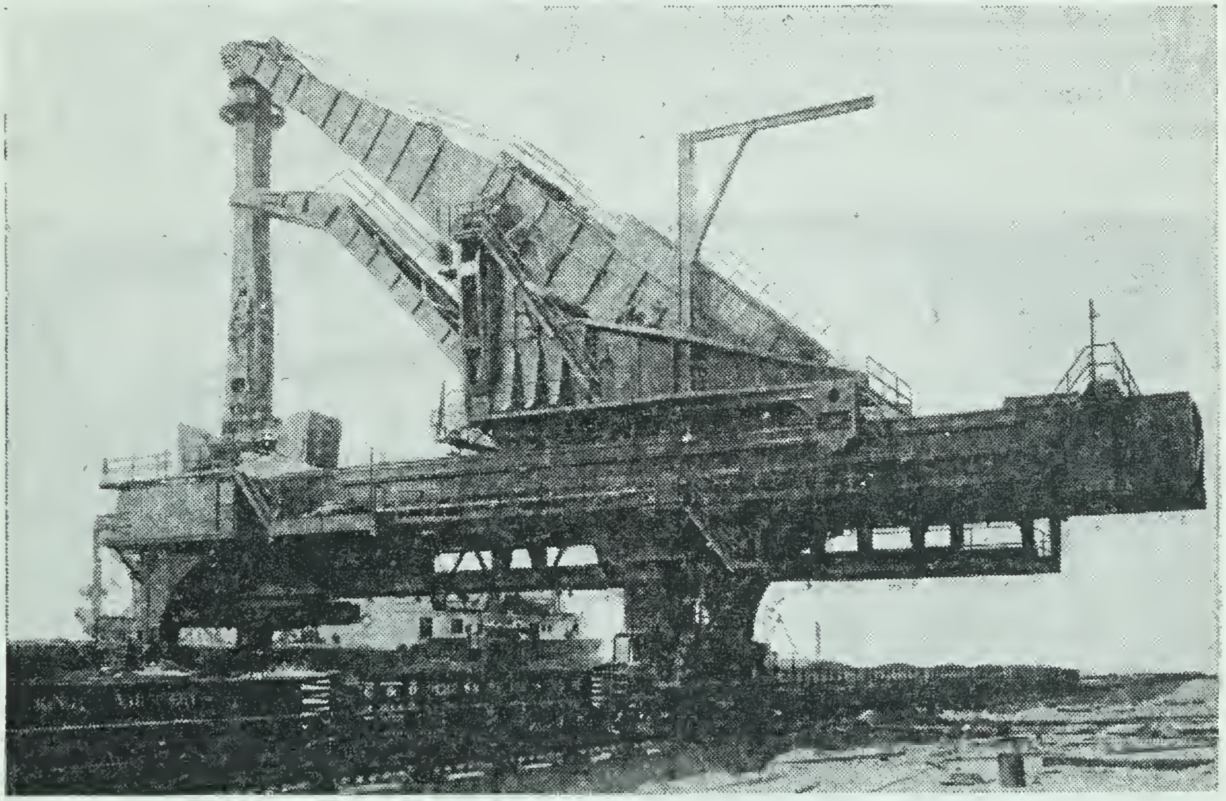
Courtesy of Dayton C. Miller, Case School of Applied Science

FIG. 3–6. The Rueprecht balance was constructed especially for the Case School of Applied Science. Under a load of 1000 gm., this balance is sensitive to 0.000,002 gm. The balance may be counterpoised when two one-lb. weights are placed side by side on one side of the balance. If one of the weights is then placed on top of the other, thus removing it slightly farther from the center of gravity of the earth, the balance is sensitive enough to show a reduction in weight.

D. WORK

1. WHEN A FORCE MOVES MATTER, WORK IS DONE

Work is an accomplishment. If a man holds a weight of 100 lb. on his shoulder all day long, he is merely exerting force, but in the *scientific sense* he is not doing any work. He does work in lifting the weight to his shoulder. If a man tugs at a 5-ton truck and does not move it, he is not doing any work. *If a force acts upon a body and moves it, then it is said to do work upon the body.* (See Fig. 3–7.) Usually a man is not paid for his *effort*, but for the *effect produced*, or the *work accomplished.*



Courtesy of the Wellman Engineering Company

FIG. 3–7. Such gigantic cranes unload from 10,000 to 12,000 tons of iron ore in four or five hours.

2. WORK IS MEASURED IN FOOT–POUNDS

Work equals force multiplied by distance. In measuring work, we use the same units as are used in measuring energy. The amount

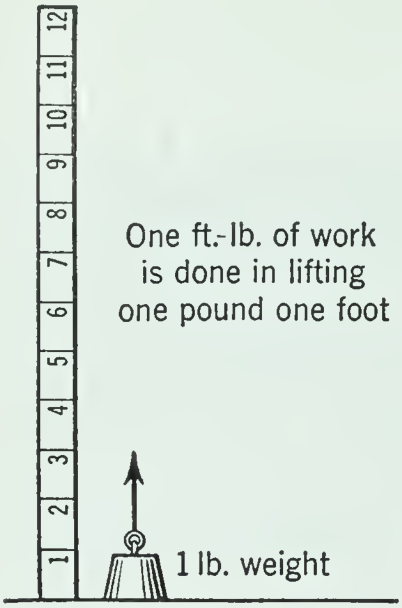
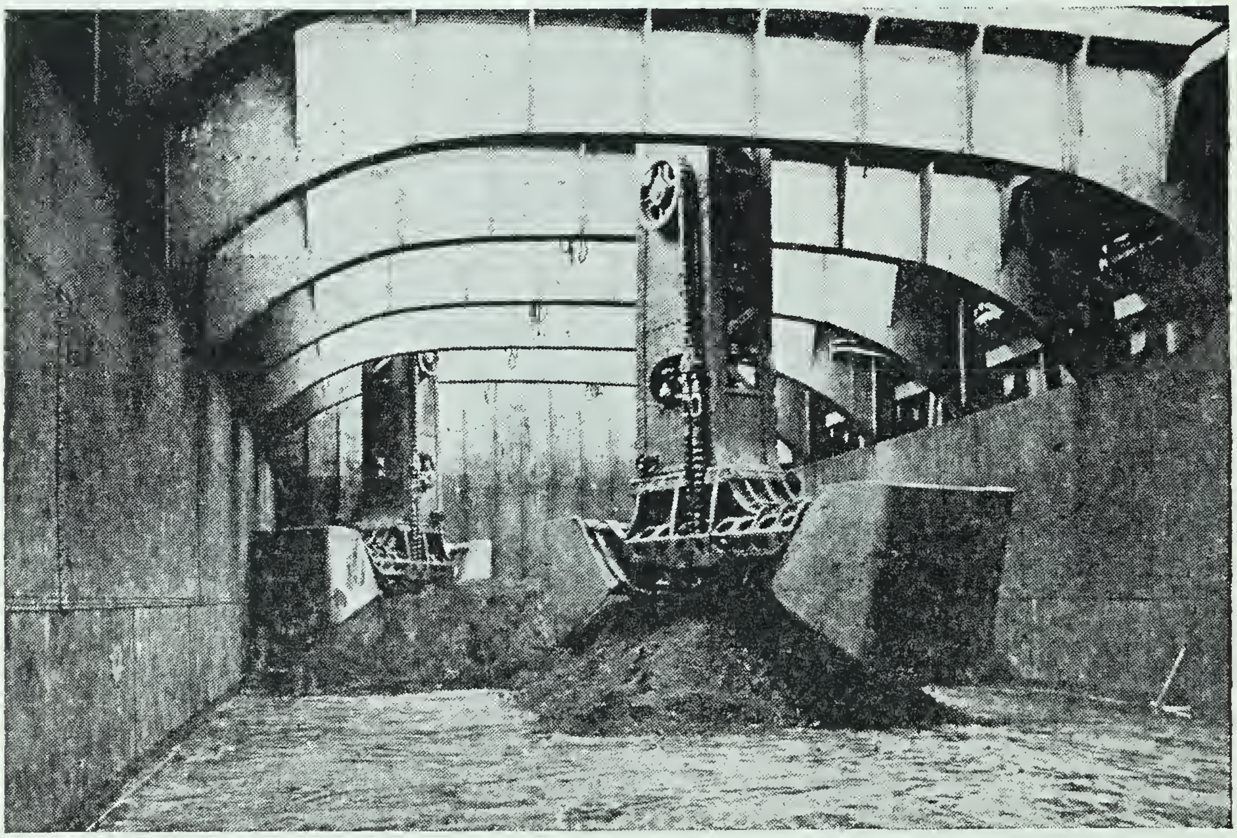


FIG. 3–8. Work done in lifting a weight equals weight times vertical distance.

of work done is equal to the product of *force times distance.* If either the force or the distance is zero, no work is done. If one pound of force acts through a distance of one foot, it does one *foot-pound* of work. This unit of work almost defines itself. (See Fig. 3–8.) A man who weighs 160 lb. does 1600 ft.-lb. of work in climbing a flight of stairs 10 ft. high. He lifts his own weight 10 ft. against the force of gravity. When an object is lifted *vertically,* the amount of work done is always equal to the *weight of the object* times the *vertical height* through which it is lifted. The reason for this is apparent, since one must use a force of 100 lb. to *lift* a weight of 100 lb. The ore



Courtesy of the Wellman Engineering Company

FIG. 3–9. The clam-shell buckets hold from 10 to 15 tons of ore. Compare their size with that of the man in the peephole in the center of the picture. The huge boats used to carry iron ore are little more than steel shells.

unloader of Figure 3–9 works rapidly; it can remove 15 tons of ore per bucketful. Boats containing 13,000 tons of iron ore have been unloaded in 4.5 hours.

If we *drag* a trunk weighing 150 lb. across a platform 20 ft. long, the amount of work done is less than the product of the weight and the distance. To slide the trunk, all the force that is necessary is enough to overcome the friction. If the force necessary to overcome friction is 45 lb., the amount of work done is therefore equal to the force (45 lb.) × the distance (20 ft.), or 900 ft.-lb. (See Fig. 3–10.) To carry the same trunk up a flight of stairs 20 ft. high, one would have to do 3000 ft.-lb. of work. In all cases, the following is true:

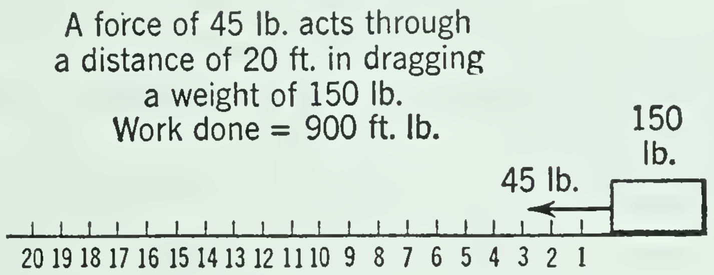


FIG. 3–10. It takes less work to slide a weight a given distance than it does to lift it an equal distance.

work = force × distance

In the metric system, one may use the *gram-centimeter* as a unit for measuring work, or the *kilogram-meter*. The amount of work done by a force of *one gram* acting through a distance of *one centimeter* is *one gram-centimeter*. The amount of work done by a force of *one kilogram* acting through a distance of *one meter* is a *kilogram-meter*.

DEMONSTRATION. Is the same amount of work required to lift a weight 100 cm. as to slide the same weight 100 cm.? Using a meter stick to measure the distances, by means of a spring balance lift a 500 gm. weight vertically 100 cm. from the surface of the table. How much work (gm.-cm.) was done on the weight? Now, by means of the balance, tow the weight 100 cm. along the surface of the table. What force was necessary to slide the weight? What work was done in sliding the weight 100 cm.? Compare the two work calculations.

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E. POWER

1. IT IS THE RATE OF DOING WORK

Power depends on force, distance, and time. Too often we think of work as anything which makes us tired, but we know that the term *work* cannot be so used in physics. We may also need to revise our concept of the word *power*. We call a man "powerful" when he is capable of exerting great force.

An employer is interested not only in having a job of work completed, but also in how much time is spent in doing it. In transportation the most important factors are: (1) the size of the load which can be transported by the automobile, truck, train, or airplane; and (2) the speed with which the load can be transported.

A small outboard motor could drive a destroyer but with a speed so slow that we could hardly see the motion. To do any job faster it is necessary to expend more energy in a given time; for this reason some fast trains and ocean liners charge an extra fare. It requires more fuel per mile to produce extra energy for increased speed. Likewise more energy, hence more fuel, is required to maintain a given speed if the load is increased. Speed here means miles per hour or feet per second. In speaking of the number of airplanes produced per day by an aircraft manufacturer we refer to speed as the rate of production. The amount of coal consumed per hour by a locomotive is called its rate of fuel consumption. In mechanics we consider the *rate of doing work* when we use the term *power*.

When we speak of force, we are interested in one magnitude only, because *force is independent of both distance and time.* We must consider two things when we speak of work: force and distance. *Work is independent of time.* A man does the same amount of work when he climbs a flight of stairs in one minute that he does if he climbs the same flight of stairs in one hour, *but he does not use the same amount of power. Power depends upon three factors: the force exerted, the distance the force moves, and the time required.* We may define power as *the rate of doing work.*

2. HOW IS POWER MEASURED?

Power may be measured in foot-pounds per second (horsepower). In a series of experiments, James Watt, the inventor of the steam engine, found that an English dray horse could continue for a reasonable length of time to work at the rate of 550 *ft.-lb. per sec.* In the English system, the *horsepower* is the unit of power; it is equal to 550 ft.-lb. per sec., or 33,000 ft.-lb. per min. (See Fig. 3–11.) Some automobile engines develop more than 100 horsepower. The U. S. Army Air Force Thunderbolt (known officially as the P-47) carries a 2000-horsepower Pratt and Whitney engine. Several steam turbines have been built which develop over 200,000 horsepower each. The power of the average man is about 78 ft.-lb. per sec. It is true that almost any adult person can work at the rate of one horsepower for a few seconds. A boy who weighs 110 lb. could probably run up a flight of stairs 20 ft. high in 4 sec. That means that he is developing one horsepower. He might possibly climb a second flight of stairs at the same rate. Do you think that he could continue to run at the same rate up ten flights?

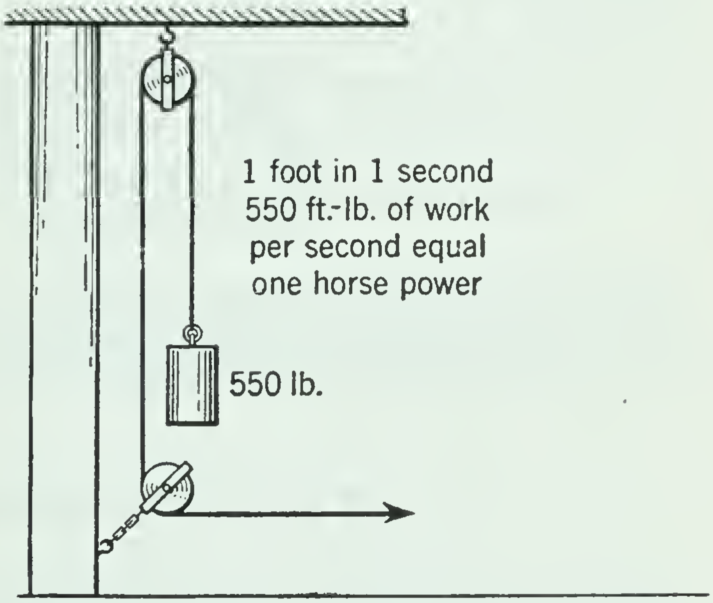


FIG. 3–11. How to determine horsepower.

Power may be measured in watts and kilowatts. In the metric system the watt and the kilowatt are used as units for measuring power. *The watt is equal to about 10,200 gram-centimeters per second. The kilowatt equals 1000 watts.* The horsepower (H.P.) is equal to 746 watts. Hence the horsepower is approximately $\frac{3}{4}$ of a kilowatt. For example, a 15-K.W. engine is about 20 H.P. A 100-H.P. engine can lift a car weighing 4000 lb. to a height of

825 ft. in one minute. The kilowatt is generally used as a power unit in measuring electricity.

$$\text{H.P.} = \frac{\text{total work in ft.-lb.}}{550 \times \text{time in sec.}}$$

$$\text{or, H.P.} = \frac{fs}{550t}$$

Problem. What horsepower engine is required to hoist 100 tons of coal per hr. from a mine 200 ft. deep?

Solution.

$$\text{H.P.} = \frac{\text{total work done (in ft.-lb.)}}{550 \times \text{time in seconds}}$$

$$\text{Then, H.P.} = \frac{100 \times 2000 \times 200}{550 \times 60 \times 60}; \text{ the answer is 20.2 H.P.}$$

Demonstration. Measure the height (vertical) of a stairway. Using a stop watch, time (by seconds) several boys running up the steps. Obtain the weight of each boy; then calculate the horsepower which he developed.

3. TRANSMISSION OF POWER

As power is generated or produced it must be transmitted to the place where it is to do the work. In the automobile the power of the motor must be sent to the rear wheels; in an ocean liner from the steam turbines to the propellers; in a machine shop from the electric motor to the lathe or saw; and in the bicycle from the pedal to the rear wheel. Very shortly we shall study some of the methods of power transfer.

F. WHAT IS A MACHINE?

1. A DEVICE THAT TRANSFERS OR TRANSFORMS ENERGY

Examples. We have already said that a machine enables us to use our own energy more efficiently and also enables us to make use of other sources of energy. But a machine does even more than that. It is through the use of various types of machines that any one of the five forms of energy — heat, light, electrical, chemical, and mechanical — can be transformed into any one of the other four. (See page 41.) For example, a steam engine converts heat energy into mechanical energy; the gasoline engine converts the chemical energy of gasoline into mechanical energy; either of these engines could be used to drive a generator which would change the mechanical energy into electrical energy. After the gasoline engine of an automobile has transformed chemical energy into mechanical energy the latter must be transmitted to the wheels of the car. Whatever the means used to transmit mechanical energy from one place to another, it involves the use of some kind of machine. A machine, therefore, may be defined as a device used to transform or transfer energy.

2. ALL MACHINES ARE MODIFICATIONS OR COMBINATIONS OF SIX SIMPLE MACHINES

Six simple machines. The six simple machines are: the *lever*, the *pulley*, the *wheel and axle*, the *inclined plane*, the *screw*, and the *wedge*. Other machines are either modifications of one of these simple machines or combinations of two or more of them. It is also quite easy to show that the pulley and the wheel and axle are really levers, and that the wedge and the screw are inclined planes. All machines are modifications or combinations of these six simple machines.

Demonstration. Show an example of the lever, the pulley, the wheel and axle, the inclined plane, the screw, and the wedge.

How can power be transmitted? If one looks around a machine shop, he observes two types of machines: (1) *Driven machines;* (2) *Driving, or "power" machines.* How are the "power" machines connected with the driven machines, such as lathes, planers, grinding and polishing wheels, and saws? Several methods are in use. In the older shops, belts and pulleys were much used. If a belt is used as shown in Figure 3–12, both the *drive* wheel and the *driven* wheel will turn in the same direction. If the belt is crossed,

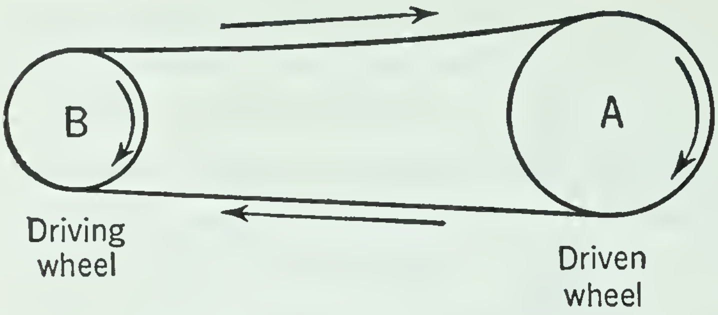


Fig. 3–12. Both wheels turn in the same direction.

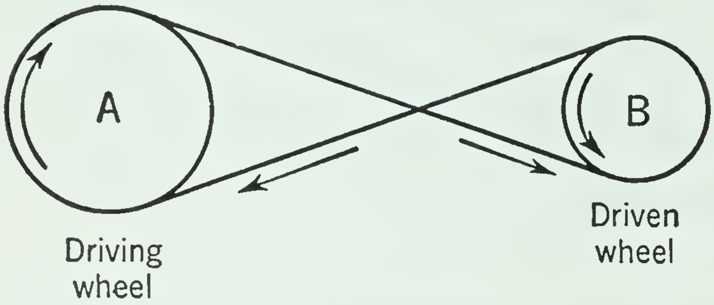


Fig. 3–13. With such a belt transmission, the driving wheel and the driven wheel turn in opposite directions.

as in Figure 3–13, then the wheels turn in opposite directions. The ratio of the speeds at which belt wheels rotate is *inversely* proportional to the circumferences of the wheels. For example, if wheel *A* has a circumference of 10 in. and wheel *B* a circumference of 5 in., then *B* will make *two* revolutions while *A* is making *one*.

In a study of the bicycle, we learn that a chain is used to transmit the power from the wheel to which the pedals are attached to the small sprocket wheel attached to the rear wheel. (See Fig. 3–14.) In most modern shops, an electric motor is used to drive the machines. The power is transmitted to the motor from the electric generators by the use of insulated electric cables.

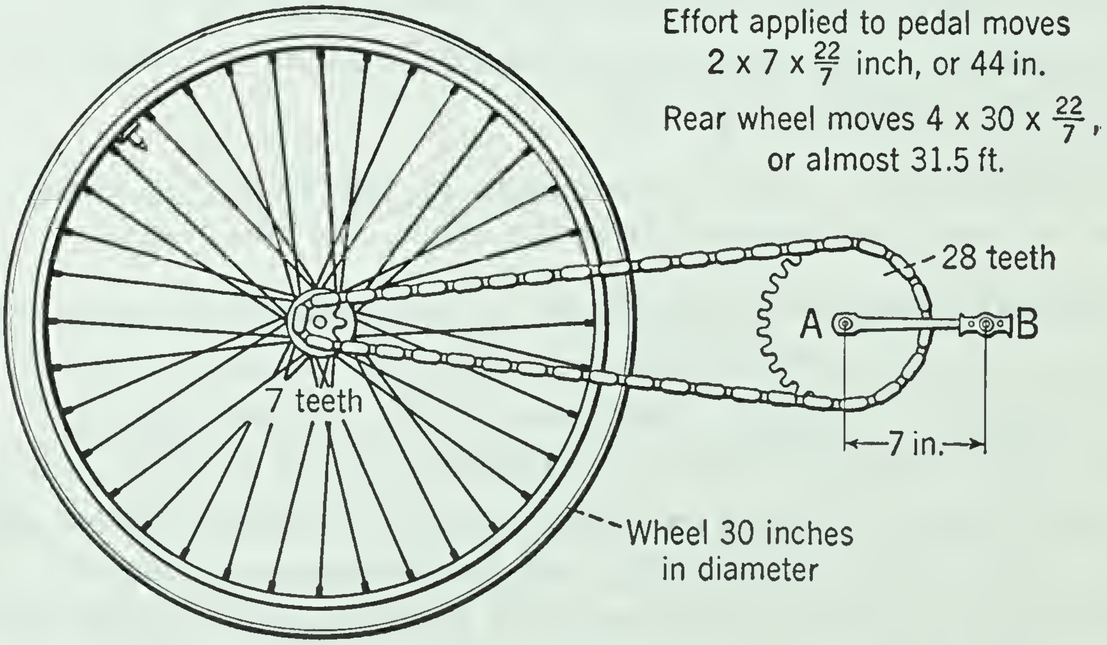

Effort applied to pedal moves $2 \times 7 \times \frac{22}{7}$ inch, or 44 in.
Rear wheel moves $4 \times 30 \times \frac{22}{7}$, or almost 31.5 ft.
28 teeth
A
B
7 teeth
7 in.
Wheel 30 inches in diameter

Fig. 3–14. The bicycle has a mechanical advantage of speed.

The power may also come from a steam engine or a gasoline engine. In the automobile, the power from the engine is transmitted through the clutch, the transmission gears, the drive shaft, and the differential to the rear axle.

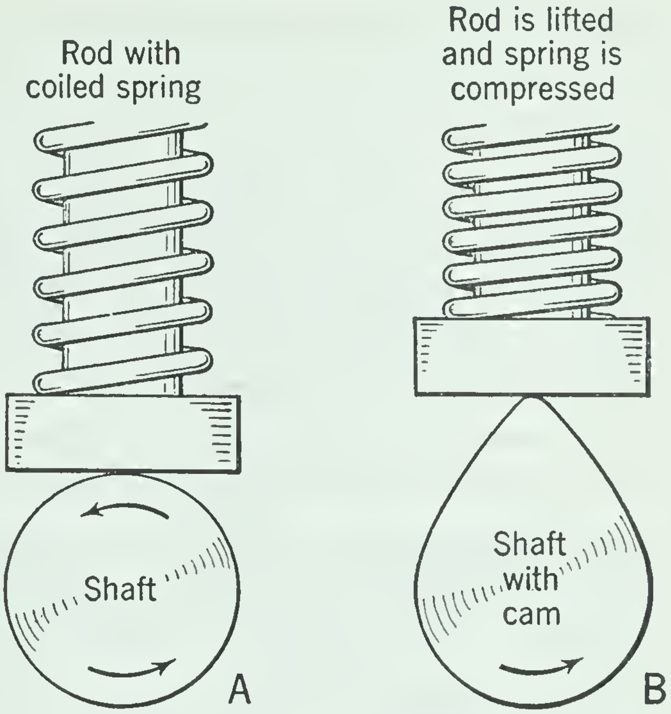


FIG. 3–15. The cam changes a rotary motion to an up-and-down motion.

Why do we have cams or eccentrics? In the transmission of power, it is very often desirable to change a *rotary* motion into *up-and-down* motion, or vice versa. To accomplish this purpose, we use a *cam* or *eccentric*. Let us refer to Figure 3–15 in our study of the cam. If the circular shaft shown at *A* rotates, it slides around under the vertical rod, but it does not move it up and down at all. The shaft at *B* has a projection on one side, which lifts the rod as it slides past the end and lets it spring back after it has passed. Thus the rod moves up and down as the shaft rotates. Such a device is called a *cam*. Because the projection is off center, it is sometimes called an *eccentric*, from the Latin words meaning "from center."

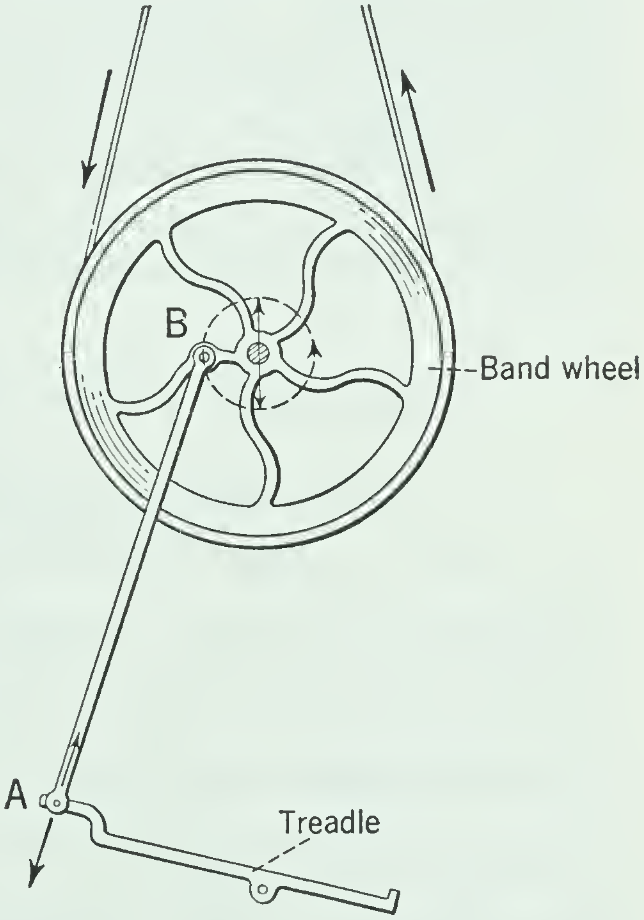


FIG. 3–16. Band wheel and treadle of sewing machine.

It would be most awkward to try to move the feet in a circle to drive the band wheel of a sewing machine. It is easy to move the treadle up and down. (See Fig. 3–16.) Notice that one end of the connecting rod is fastened at B, a point which is *off center* on the band wheel, and that the other end is fastened to the treadle at A. As we push down with the toe, the end of the rod A moves downward and pulls the end B around in almost a semicircle. It will stop at *dead center* when we keep on pushing downward; but, if we hesitate, the inertia of the band wheel will carry it on past the *dead-center* position. As we push down with the heel, A now moves upward and pushes B up along the other semicircumference. There it reaches another dead-center position, and we need to hesitate again to let inertia carry B past this position. Thus we push down with the toe, hesitate, push down with the heel, hesitate, and so on, as we operate the treadle of a sewing machine. The effort moves up and down and has what is called a *reciprocating* motion, but a rotary motion is imparted to the band wheel. By means of a belt, the power is transmitted from the band wheel to the hand wheel, which in turn controls another eccentric that causes the needle to move up and down. The automatic bobbin winder is another example of the principle of the cam. We shall also find that the cam is used to control the valves of the steam engine and the gas engine.

G. THE LAW OF MACHINES

1. WORK INPUT EQUALS WORK OUTPUT

$E \times De = R \times Dr$. Input equals output. From the law of conservation of energy (see page 44) we learned that energy cannot be made or created; neither can energy be destroyed. If a certain amount of energy is put into a machine, even though the machine might change the form of the energy that same amount of energy should be obtained from the machine. If friction could be eliminated, this would be true of all machines. In all frictionless machines, the *effort* (E) *multiplied by the distance the effort moves* (Ed) *equals the resistance* (R) *multiplied by the distance the* *resistance moves* (Rd). This statement is known as the *Law of Machines.* It can be written also in this form:

$$E \times Ed = R \times Rd$$

The effort times the distance it moves equals the *work* put into the machine, or the *input.* The resistance times the distance it moves equals the work accomplished by the machine, or its *output.* If we *disregard friction and weight of parts, input equals output.*

2. MECHANICAL ADVANTAGE

Mechanical advantage is the number of times a machine multiplies force. Man often uses a machine to multiply his feeble efforts. Such a machine gives him an advantage. Suppose we assume a frictionless machine in which an *acting force* of 1 lb. can exactly counterbalance a *resisting force* of 5 lb. We say the *mechanical advantage* of that machine is 5, because the resisting force is five times as great as the acting force. Let us call the resisting force the *resistance* R, and the acting force the *effort* E. Then the mechanical advantage (MA) equals $\frac{\text{resistance}}{\text{effort}}$.

$$MA = \frac{R}{E}$$

The mechanical advantage of any machine may also be found by measuring the distance the effort moves and the distance the resistance moves in the same time.

$$MA = \frac{\textit{distance effort moves}}{\textit{distance resistance moves}}$$

In all the simple machines we shall use the term *mechanical advantage* frequently. There are two ways in which this mechanical advantage can be found. (1) By the use of a spring balance, the *acting force* E can be measured and also the *resisting force* R. Then the mechanical advantage equals $\frac{R}{E}$, providing friction is disregarded. (2) With a ruler we may measure the *distance the effort moves*, De, and also the *distance the resistance moves*, Dr. In this case, $MA = \frac{De}{Dr}$. The formula $MA = \frac{R}{E}$ tells what a machine should do theoretically, that is, disregarding both friction and the weight of parts. The formula $MA = \frac{De}{Dr}$ is often more convenient.

What is *MA* of speed? Instead of using a machine to multiply effort, we sometimes use it to multiply speed. In this case the distance the effort moves is less than the distance the resistance moves; therefore the mechanical advantage is a number less than one. In the bicycle of Figure 3–14, $MA = \frac{44}{31.5 \times 12} = 0.116$.

H. EFFECT OF FRICTION IN MACHINES

1. FRICTION REDUCES THE WORK OUTPUT

What is friction? *The resistance to any force trying to produce motion we call friction.* If we attempt to roll or slide one body over another, friction opposes us. To some extent it is due to adhesion, but it is largely caused by irregularities in the surfaces of the two bodies. Uneven surfaces tend to interlock and offer resistance to motion. Friction between smooth plane surfaces is much less than it is between roughened surfaces. Friction is generally classified as either *sliding friction* or *rolling friction.*

What is the coefficient of friction? Let us weigh a block of wood and then hook a spring balance to it so that it may be pulled along the table. (See Fig. 3–17.) The reading of the spring balance is much less than the weight of the block. It takes less force to slide one end of a piano than it does to lift it. The ratio of this "force of friction" to the weight of the block is called the *coefficient of friction.*

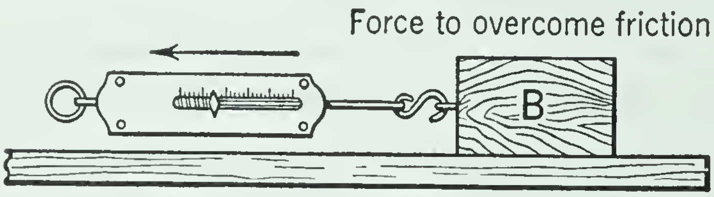


FIG. 3–17. Measuring the force needed to overcome sliding friction.

$$CF = \frac{\text{force to overcome friction}}{\text{weight}}$$

Suppose that the block weighs 100 gm., and it needs a force of only 30 grams to keep the block in uniform motion. Then the coefficient of friction is $\frac{30}{100}$, or 0.3. The coefficient of friction varies with the nature of the material and the degree of polish of the surface. The coefficient of friction of iron sliding on iron is less than that of wood sliding on wood.

2. REDUCING FRICTION

Several common methods to reduce friction. Several methods of reducing friction are in common use. To have a machine that is free-running and has little friction, the manufacturer or the operator may do one or more of the following things:

(1) *Polish the bearings.* If a wheel is to turn easily on an axle, both the contact surfaces, called bearings, must be polished to a glasslike smoothness. The material, too, must be so hard that it will not wear away rapidly or become grooved easily.

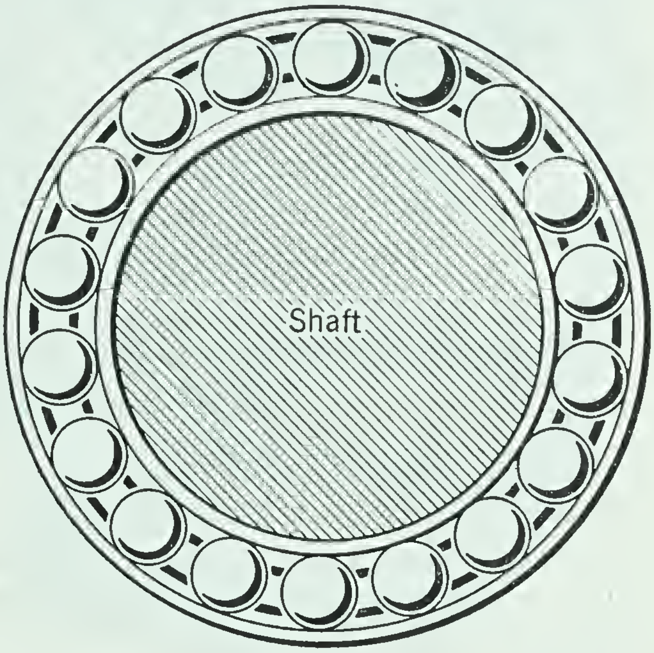
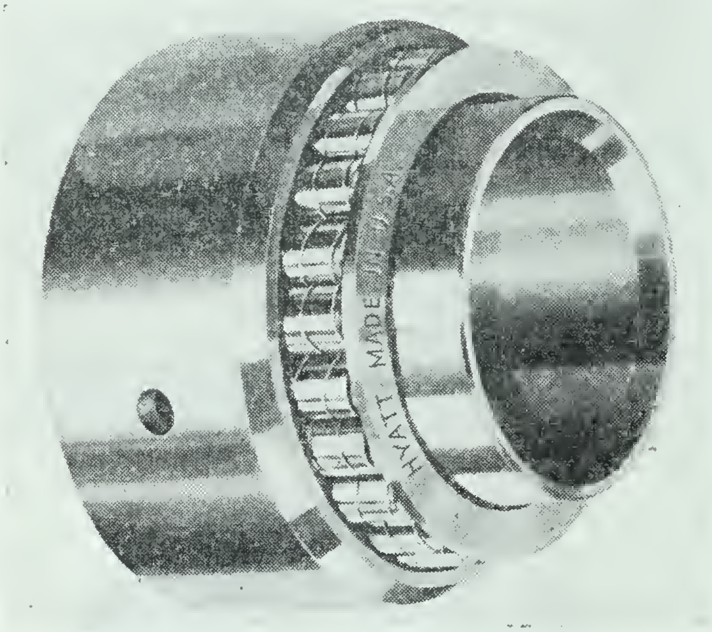


Fig. 3–18. Ball bearings are used to reduce friction.

(2) *Use antifriction metals.* When steel slides over an alloy of lead and antimony, the coefficient of friction is less than when steel slides over steel. Bearings are sometimes packed with such an alloy to reduce friction. The alloy is known as *antifriction metal,* and the process is called *babbitting,* from the inventor, Babbitt.

(3) *Use ball bearings or roller bearings.* The coefficient of friction of steel balls rolling on steel may be as low as 0.002, only

about 0.01 as much as that of steel sliding on steel. (See Figs. 3–18 and 3–19.) We put casters on beds and other furniture to make use of rolling friction. If one surface is soft, then rolling friction may be high. A sled may slide over the snow more easily than a vehicle on wheels may be pulled through deep snow. Figure 3–20 shows how a wheel which sinks deeply into soft earth encounters great friction. As it advances, it continually has to break down a shoulder of earth. Tapered roller bearings (Figs. 3–21 and 3–22) are much used in automobile bearings. They are especially strong in resisting sidewise thrusts.



Courtesy of the Hyatt Roller Bearing Company

Fig. 3–19. Flexible roller bearings are used to reduce friction.

(4) *Use a lubricant.* If oil, for example, is used as a lubricant, an oil film flows between the bearing surfaces, separating them so that *fluid* friction is substituted for *solid* friction. The most common lubricants are oils, grease, graphite, and wax. Paraffin and soap are good lubricants for wood. A good lubricant should have the following characteristics: (*a*) It must have just sufficient body so that it will not be squeezed out of the bearing by the weight of the parts. (*b*) It must not evaporate. (*c*) It must not corrode or

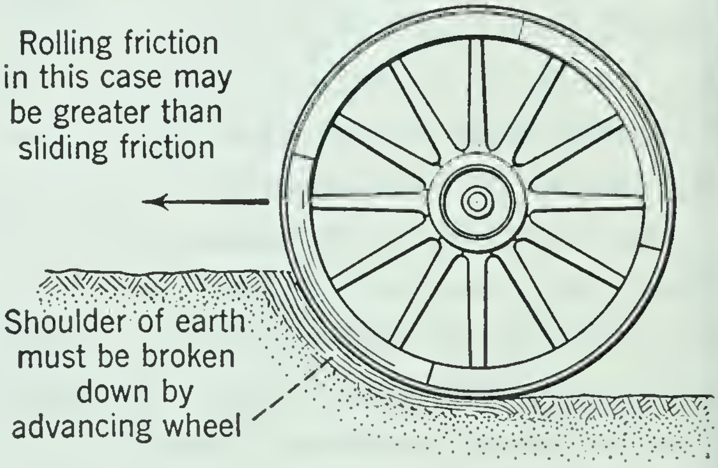
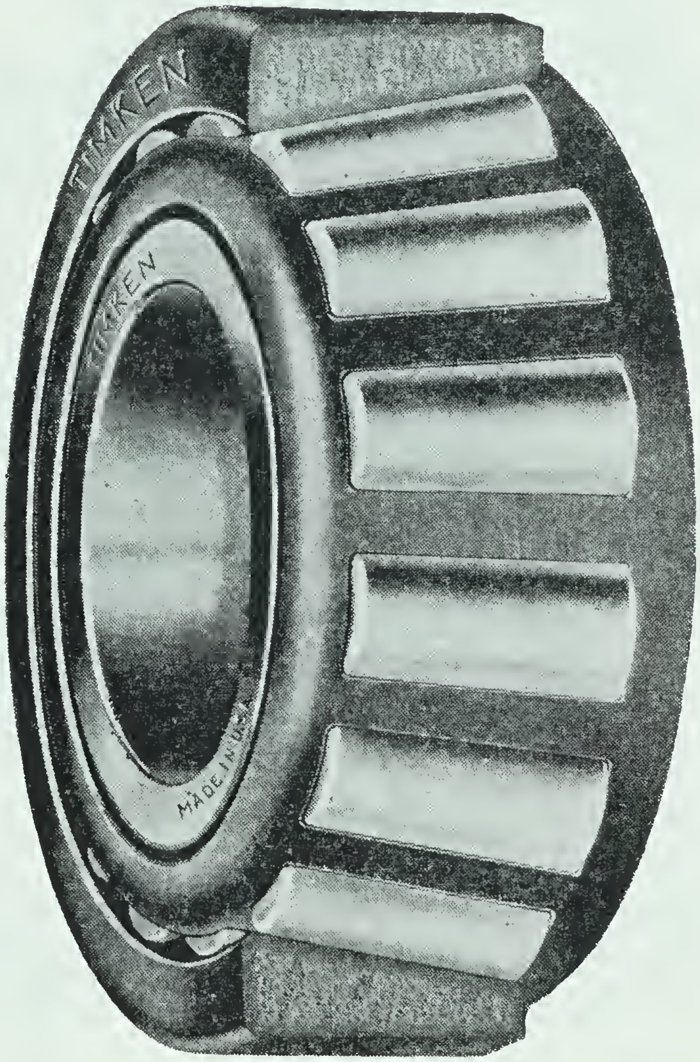

Rolling friction in this case may be greater than sliding friction
Shoulder of earth must be broken down by advancing wheel

Fig. 3–20. Rolling friction in some cases is very great.

rust the bearings. (*d*) It must be free from hard, gritty substances. (*e*) It should not be too much affected by temperature. It is possible to judge the viscosity of oils for use as lubricants by letting metal balls fall through tubes filled with the oils to be tested. The thickness of the oil can be judged by the amount of time it takes for the balls to fall through the different oil samples.

In those cases where an object is to be moved or where a resisting force is to be overcome, friction is a disadvantage. An axle upon which a wheel must turn is highly polished and then oiled to reduce friction. In all the bearings of a sewing machine, a bicycle, an automobile, or any other machine, efforts are made to reduce friction to a minimum.

Although friction has been greatly reduced in the moving parts of machines, it cannot be completely eliminated. For this reason the total work produced by a machine is always less than the total work put into it, or work input is greater than work output.



Courtesy of the Timken Roller Bearing Company

FIG. 3–21. The tapered roller bearing makes a strong bearing of low friction.

DEMONSTRATION. How does the force due to sliding friction compare with the force due to rolling friction for the same weight? Pull a block of wood across the table with a spring balance. Note the effort in grams. Place some round pencils under the block and repeat. Compare the two

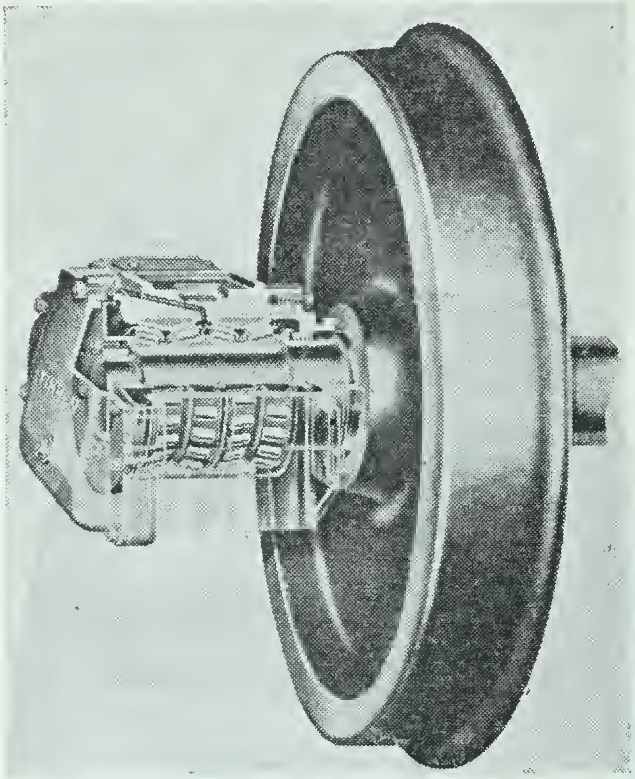

Courtesy of the Timken Roller Bearing Company

Fig. 3–22. Roller bearing used on locomotives and cars.

forces required. Name the two types of friction illustrated.

Demonstration. Exhibit samples of bearings, such as a crankshaft or connecting-rod bearings, ball bearings, and roller bearings.

3. FRICTION IS USEFUL

How does friction help us? You have seen a driver trying to start a car on icy streets. The rear wheels spin around, but the car does not move. There must be friction between the tires and the pavement before one can move a car. A horse cannot pull a wagon unless friction furnishes him a secure foothold. Without friction, we would be unable to walk. It is difficult to walk on ice, but even the smoothest ice has some friction. When we apply the brakes to stop a moving car, we depend upon friction to aid us. (See Fig. 3–23.) The caterpillar tractor can pull heavy loads over soft ground or through the snow because the projections on the treads increase friction. (See Fig. 3–24.)

Friction also helps us in less obvious ways. We screw a hook into the ceiling. If there were no friction, it would immediately

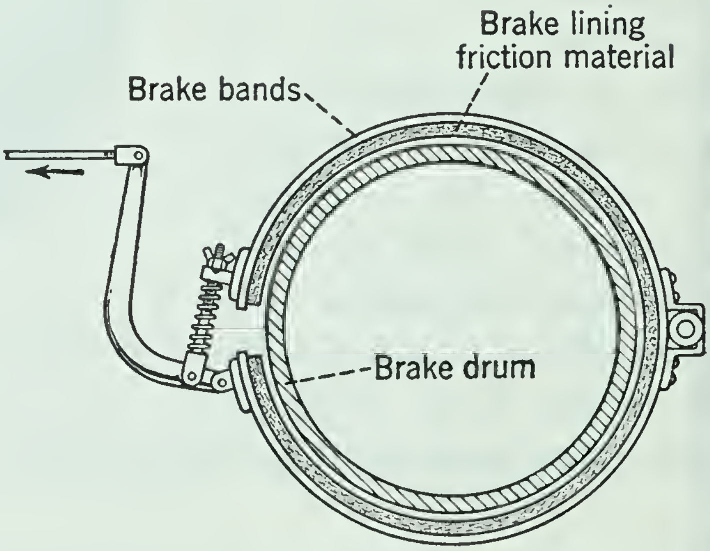


Fig. 3–23. Brake bands are lined with friction material. They stop a car by contracting around the brake drum, or by expanding against the inner rim of the drum.

fall out of its own weight. Without friction, a nail driven into a board would not hold at all. Our dishes would slide off the table if the table were not perfectly level, provided friction were missing.

Fluid friction is less than solid friction. Everyone knows that an automobile skids more easily on a wet pavement than it does on one that is dry. We know that oil makes a machine run more easily. It is generally true that *fluid* friction is much less than *solid* friction. To prove that there is a difference you might try rowing a boat in the water and then try to row the boat over the sand on the beach.

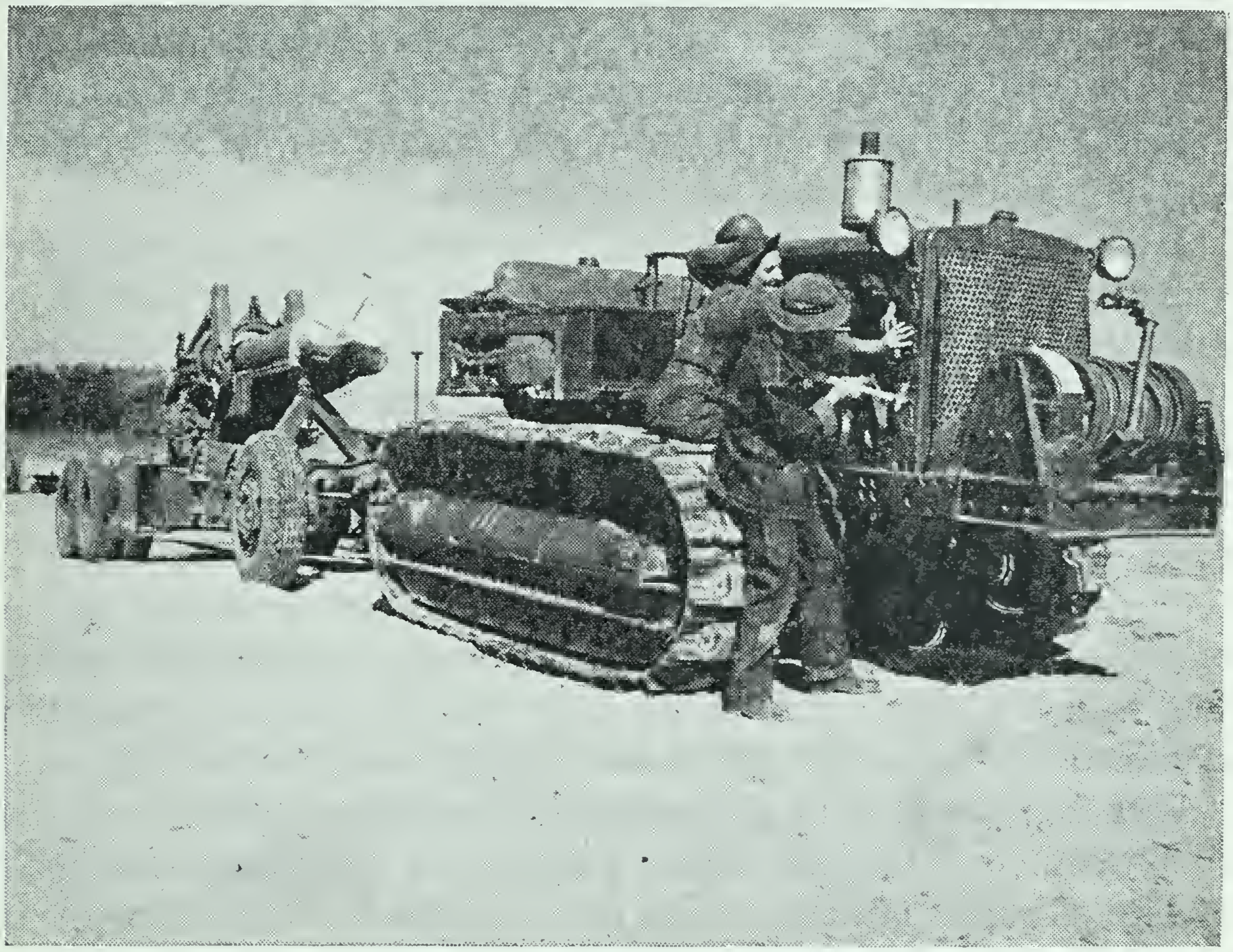


Photo by U.S. Army Signal Corps

FIG. 3–24. Ten-ton caterpillar tractor with winch pulling a 155 mm. gun.

While sliding friction is fairly independent of velocity, fluid friction varies greatly with the velocity. At moderate speed, fluid friction is nearly proportional to the square of the velocity. Air being a fluid, air resistance increases with an increase of velocity. It is estimated that a modern automobile traveling 40 m.p.h. uses over 7% of its fuel energy in overcoming air resistance. At 20 m.p.h. the air resistance is only one-fourth as much. An ocean liner such as the *George Washington*, which crossed the Atlantic in 10 days, despite the fact that the passengers had to be fed for twice as many days, could afford to carry passengers at a lower rate than the *Queen Mary*, which made the trip in 4.5 days. A destroyer may be only one-tenth as heavy as a modern battleship, but its engines must develop nearly as much horsepower, since its speed may be 15 or more knots per hour greater.

How can we increase friction? The engineer of a locomotive sometimes sands the rails to increase the friction or traction so that the drive wheels will not slip. Sand is used on streetcar tracks and icy hills in winter. Chains are put on the rear wheels of automobiles to enable the tires to grip the pavement without skidding. In various sports and occupations, men wear rubber-soled shoes or have the soles studded with spikes or cleats to prevent slipping. The violinist rosins his bow to increase friction, and a baseball pitcher dips his fingers into a rosin bag to enable him to get a better grip on the ball. The brakes of automobiles are lined with material which has a high coefficient of friction.

What are the laws of sliding friction between solids? In scientific work, one depends upon experiment. By such methods, several so-called laws of *sliding friction* have been developed. In most cases they are only approximations, with many more exceptions than are common to most laws of physics.

(1) If we hook a spring balance to an object, and pull horizontally, we find that it takes more force to start the object sliding than it does to keep it sliding. We conclude that *sliding friction is greater at starting.*

(2) In a similar manner, we do not find that sliding friction is much greater if we run and pull a sled than it is if we walk along slowly. In such a case, we conclude that *sliding friction is independent of the velocity*, but it is a well-known fact that the friction of the brake shoes against the wheels of a train running 60 miles

per hour is probably at least one-third more than when the train is running 20 miles per hour.

(3) If we have a brick lying on its side on a table, we find that the force needed to keep it sliding is almost the same as if the brick were lying on one edge or standing on end. Hence we conclude that *the force of friction is practically independent of the area of contact between the surfaces.*

(4) It does not require so much force to slide an empty chair across the floor as it does to slide the same chair when a 200-lb. man is sitting on it. *Friction is directly proportional to the weight of the object.*

4. FRICTION AND EFFICIENCY

What is efficiency? When a man rides a bicycle up a hill, he must lift his own weight and also that of the bicycle the vertical distance of the hill. Lifting the bicycle is not friction but it is really useless work. Further, he wastes some energy because of friction in the bicycle. No machine ever runs without some friction. Overcoming friction wastes work. Hence, input is always greater than output. In practice, we are more interested in what a machine *actually does* than in what it *should do theoretically.* We are concerned with the useful work that is accomplished. *The efficiency of a machine is the ratio of the useful work accomplished to the total work expended.*

$$\text{Efficiency} = \frac{\text{useful work output}}{\text{total work input}}$$

When efficiency is considered, *input equals useful work plus work done overcoming friction.* Efficiency is usually expressed in per cent. If a pupil solves 8 problems out of 10 correctly, his efficiency is 80%. If a machine has a total input of 1000 ft.-lb., and its useful output is only 800 ft.-lb., the machine is working at an efficiency of 80%.

Suppose that an effort of 40 lb. moves 20 ft. along an inclined plane and in so doing lifts a weight of 180 lb. to a height of 4 ft.

The *useful* work done equals 4 × 180, or 720 ft.-lb. The *total* work equals 40 × 20, or 800 ft.-lb. Then the efficiency equals $\frac{720}{800}$; dividing, we get a quotient of 0.90, or 90%.

If we have a machine which has a mechanical advantage of 5, a force of 20 lb. should support a weight of 100 lb. If actual experiment shows that it requires 25 lb. to put 100 lb. in motion, then the efficiency of the machine is $\frac{20}{25}$ or 80%. The additional 5 lb. of force required to counterpoise the weight of the machine itself represents wasted effort. In some machines the effort wasted may exceed the useful effort.

SUMMARY

1. Machines are devices used in the doing of work to transform energy or to transfer energy.
2. Some machines are made to multiply force, some to multiply speed, and others merely to change the direction of a force.
3. Energy is the capacity for doing work. The units of work are used to measure energy. Energy can neither be created nor destroyed. It may be transformed in practically any manner.
4. A force is a push or pull and tends to produce motion or to prevent motion.
5. When a force acts upon a body and produces motion, work is done upon that body. The foot-pound, the gram-centimeter, and the kilogram-meter are units of work.
6. Power is the rate of doing work. The horsepower, watt, and kilowatt are the units of power. The horsepower equals 550 ft.-lb. per second.
7. In dealing with force, we consider magnitude only; with work, we consider both magnitude and distance; with power, we consider magnitude, distance, and time.
8. If friction is neglected, for all machines work input equals work output.
9. Mechanical advantage for any machine is represented by the ratio of the distance the effort moves to the distance the resistance moves.

10. Friction is the resistance to any force trying to produce motion. It is sometimes an advantage and sometimes a disadvantage.

11. The efficiency of a machine is the ratio of the useful work accomplished to the total work expended.

How many of the following terms can you define or explain?

Work
Energy
Kinetic
Potential
Force
Power
Horsepower
Gram-centimeter
Foot-pound
Mechanical advantage
Friction
Coefficient of friction
Efficiency
Kilogram-meter

SELF-TESTING EXERCISES

Answer These Questions

On a separate sheet of paper numbered from 1 to 4 write the letters for the phrases that answer the following questions correctly.

1. In what is energy measured? (*a*) gram-centimeters; (*b*) pounds; (*c*) grams; (*d*) kilograms.
2. What is force? (*a*) a unit of work; (*b*) a push or pull; (*c*) a unit of energy; (*d*) a unit of power.
3. In what is the rate of doing work expressed? (*a*) foot-pounds; (*b*) kilograms; (*c*) horsepower; (*d*) pounds.
4. What does a machine do? (*a*) consumes energy; (*b*) multiplies effort or speed; (*c*) changes matter into energy.

Complete These Statements

On a separate sheet of paper numbered from 1 to 13 write the words needed to fill correctly the blank spaces in the following sentences.

A machine is used to . . (1) . . or . . (2) . . energy. Energy is the . . (3) . . to do work. A body in motion possesses . . (4) . . energy. Energy cannot be . . (5) . . or . . (6) . . . The complete statement of the last sentence is called the law of . . (7) . . . Work is not accomplished until a force is exerted through some . . (8) . . . Power depends upon three factors: the force exerted, the distance through which it moves, and the . . (9) . . . In all machines, if we disregard friction, . . (10) . . equals . . (11) . . . The ratio of resistance to effort in a machine is known as ..(12)... The ratio of force of friction to the weight causing the friction is called ..(13)...

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 6 write a T *or an* F *to show whether each statement is true or false.*

1. A machine may multiply effort and speed at the same time.
2. Energy may be transformed from one form to another.
3. Rate of doing work is known as power.
4. A unit of power is the watt.
5. Rolling friction is less than sliding friction.
6. Fluid friction is less than solid friction.

QUESTIONS

1. What keeps the band wheel of a sewing machine moving during the short period between the downward and upward thrusts? Compare the relative speeds of the band wheel and the hand wheel of your sewing machine.

2. How is friction an advantage in the use of a jackscrew? In what way is it a disadvantage?

3. How would you change an up-and-down motion into a rotary motion?

4. Which gives the greater braking force, brake bands acting on a 12-in. drum or on a 16-in. drum? Explain.

5. What method of power transmission has in many cases been substituted for belt drive in modern shops? How does such a change promote safety?

PROBLEMS

1. Pushing a 200-lb. box along a smooth floor requires a force of 50 lb. How much work would be needed (*a*) to push the box 3 ft.? (*b*) To lift it 3 ft.?

2. Find the potential energy of 1 cu. ft. of water at the top of Niagara Falls. (Height equals 167 ft.)

3. An automobile is traveling at a rate of 60 miles per hour. Calculate its rate of speed in feet per second. A rate of 30 miles per hour equals what rate in feet per second?

4. How much work would you do in climbing a flight of stairs 20 ft. high? What is your horsepower, if you run up the stairs in 10 seconds?

Suppose the time is 10 seconds or less; does the result show that $\frac{1}{7}$ H.P. is too low an estimate for the average man power?

5. If a horse pulls with a force of 240 lb. to keep an 800-lb. wagon moving, how much work does he do in pulling the wagon $\frac{1}{4}$ mile? If he moves at the rate of 2 mi. per hr., what H.P. does he use?

6. If each of the citizens of a city of 400,000 inhabitants uses 5 gallons of water (40 lb.) daily, what H.P. engines must be used if the height to which the water must be pumped is 100 feet?

7. The elevator in the Empire State Building makes the ascent to the 80th floor in 50 seconds. If the height is 989 ft., what H.P. is used in lifting a 200-lb. man to this floor?

8. What H.P. would you use in climbing a mountain 2500 ft. high in 30 minutes? Since you could probably walk 4 times that far in 30 minutes, give a reason why mountain climbing is so slow.

9. How many tons of ore can be lifted from a mine 900 ft. deep by an 80-horsepower engine working 24 hours?

10. In problem 1: (*a*) What is the force of friction? (*b*) Calculate the coefficient of friction between the box and the floor.

11. The coefficient of friction between sled runners and ice is 0.02. What effort will be needed to pull the sled whose combined load is 250 lb.?

12. What mechanical advantage must a machine have in order that an effort of 30 lb. may lift a 150-lb. weight?

13. In the use of a certain machine the effort moved 3 ft. while moving the weight $\frac{1}{2}$ ft. Find the mechanical advantage.

14. If the mechanical advantage of a machine is 2.5, what effort will be necessary to overcome a resistance of 100 lb.?

15. In consuming 1,500 ft.-lb. of energy a machine delivers 1,200 ft.-lb. of useful energy. Calculate the per cent efficiency of the machine.

16. A motor whose efficiency is 90% has an energy input equivalent to 6 H.P. What H.P. does the motor actually deliver?

17. A gasoline engine delivers or develops 90 H.P. If its efficiency is 85% what must be the input?

18. A 25 H.P. motor lifts a 4-ton elevator to a height of 150 ft. in 2 minutes. Calculate the efficiency of the motor of the elevator.

IV

Simple Machines

A. THE LEVER

1. TYPES OF LEVERS

Some uses of the lever. When a man rows a boat, he uses the oars as levers. We see a man using a crowbar to lift a heavy load. He is using the same kind of lever Archimedes would have used to lift the earth. The can opener, the broom, and the shovel are levers used around the house. The lever consists of a rigid bar free to turn about a fixed point called the *fulcrum*. The fulcrum is essentially the center of rotation, and the effort and resistance act upon the arms of the lever as they tend to produce rotation in opposite directions.

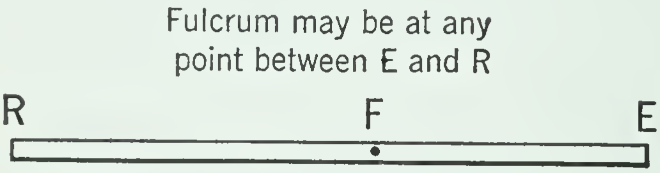


FIG. 4–1. The first-class lever.

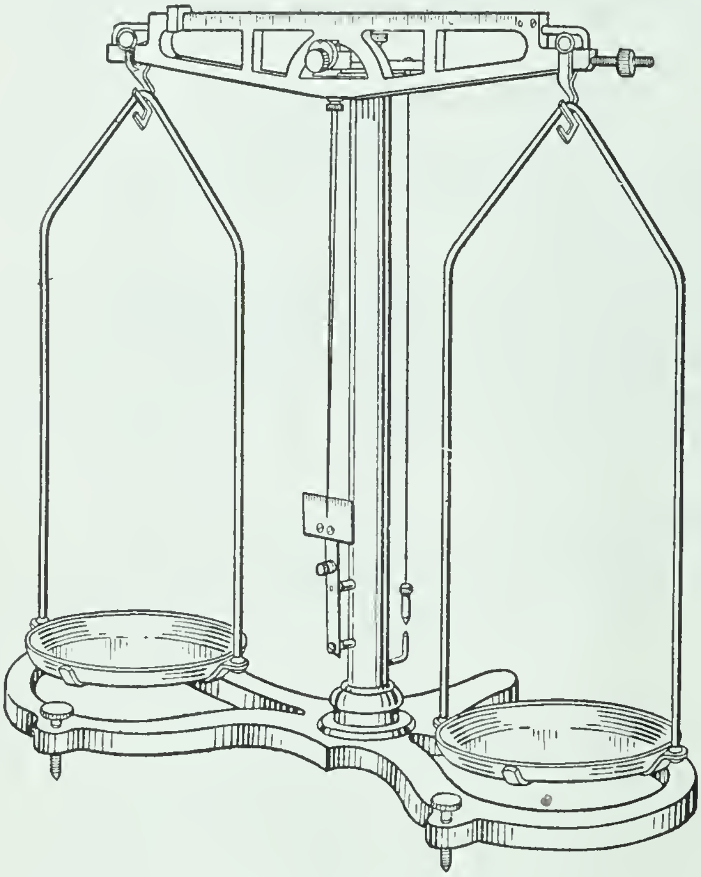


FIG. 4–2. The beam balance is a first-class lever.

What are the classes of levers? (1) With a lever it is possible to have the effort act at or near one end. The resistance is placed at the opposite end of the lever, and the fulcrum is between the two. (See Fig. 4–1.) Such a lever is known as a *first-class* lever. Such a lever may be used to gain speed, to gain force, or to change direction. The beam balance, Figure 4–2, is a common example of a lever of this class. If such a balance is well constructed, the two arms are of equal length and the light, rigid beam rests upon a very hard, knife-edged fulcrum. Accurate weighings can be made with such a balance. If *EF* exceeds *RF* in length, we have a mechanical *advantage of force.*

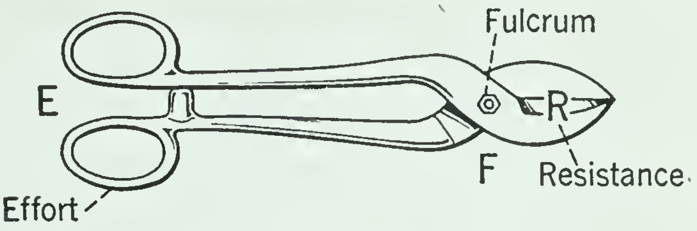


FIG. 4–3. Tinner's shears have long handles and short blades.

The tinner's shears of Figure 4–3 furnish another example. Sometimes a first-class lever is used to gain speed. Then the effort arm is shorter than the resistance arm. The force advantage is a fraction in such cases. Paper shears, or those used by a tailor, are examples. (See Fig. 4–4.)

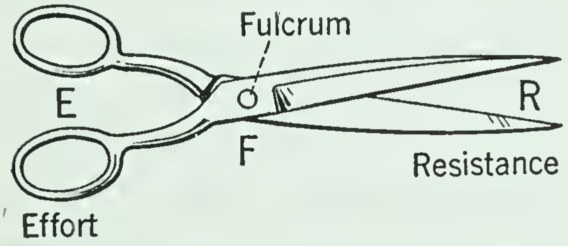


FIG. 4–4. Paper shears have short handles and long blades.

(2) Sometimes the effort is applied at one end of a lever and the fulcrum is at the other end. The resistance is placed between the effort and the fulcrum. (See Fig. 4–5.) Such a lever is known as a *second-class* lever. In a wheelbarrow, the axle of the wheel is the fulcrum. The effort is applied at the ends of the handles, and the load or resistance is between the two. (See Fig. 4–6.) Since the effort arm of a second-class lever is the *whole* lever, and the resistance arm is only a *part* of the lever, *EF* is always greater than *RF*. The mechanical advantage of such

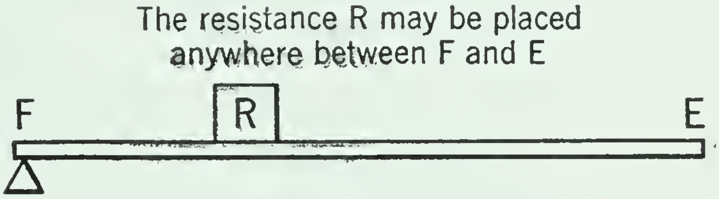


FIG. 4–5. The second-class lever.

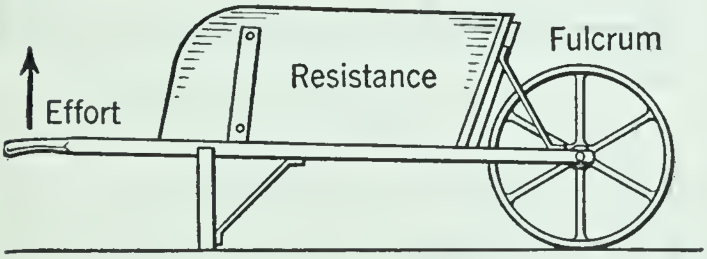


FIG. 4–6. The wheelbarrow is a second-class lever.

a lever is always *more than one.* The nutcracker and the baggage-truck are other examples of this class of lever.

If two boys carry a load on a pole between them, we may consider the pole a second-class lever and one of the boys the fulcrum. Then it is easy to find the force which the second boy must use to lift the load.

(3) When we lift a weight on the hand, we use the forearm as a *third-class* lever. The fulcrum is at the elbow. The resistance is at the other end of the lever, on the hand, and the tendons attached to the bones of the forearm act as the effort. (See Fig. 4–7.) This lever differs from the second-class lever in one way only. The positions of the effort and resistance have been interchanged. (See Fig. 4–8.) The resistance arm is longer than the effort arm; hence the resistance must move faster than the effort. Such a lever is used to gain speed. Of course we gain speed by sacrificing force. A fork, a shovel, or a broom may be used as a third-class lever; sometimes they are used as first-class levers. We find it very hard to open a door by pushing near the hinge. The resistance is *concentrated at the center of gravity* of the door, and we have been using a third-class lever. The door opens much more easily when we push near the other edge of the door, using a second-class lever, but the hand must move farther.

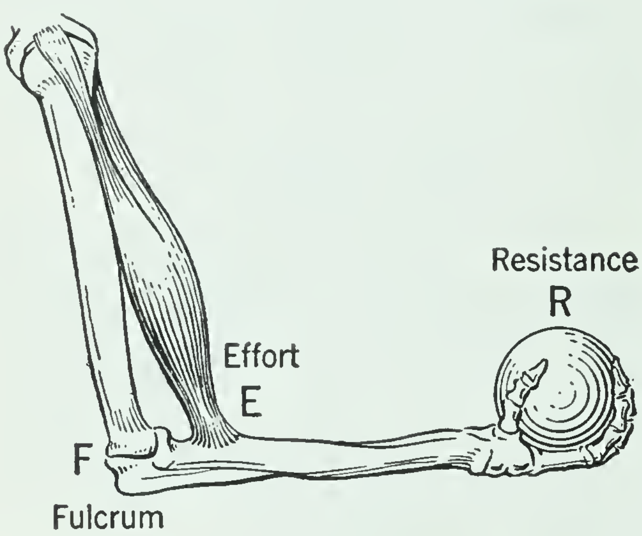


Fig. 4–7. The forearm is a lever that is much used to gain speed.

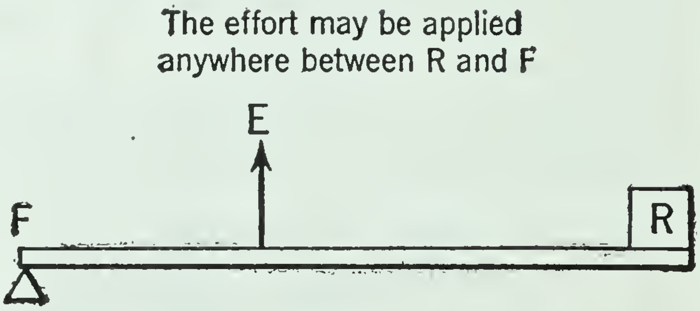


Fig. 4–8. The third-class lever.

What is the center of gravity? As a stone lies upon the ground, the earth attracts every particle of it. All these downward forces which the earth exerts are parallel. The resultant of all these parallel forces is equal to their sum, which is the weight of the stone. The point of application of this resultant is called the *center of gravity.* The center of gravity of any object is that point at which *all its weight appears to be concentrated.* If we attach a string to a stone, at a point directly above the center of gravity, and pull upward, the stone can be lifted without any rotation. An object will balance on the point of a knife placed directly beneath its center of gravity.

2. MECHANICAL ADVANTAGE OF LEVERS

How can we calculate the mechanical advantage of the lever? In Figure 4–9 we shall use the letter F to represent the fulcrum of the lever ER. At E the effort acts upon the arm EF as it tends to produce *counterclockwise* rotation. The resistance R acts upon the arm RF as it tends to produce *clockwise* rotation. While the effort moves from the point E to E', the resistance will move from R to R'. But the distance $EE':RR' = EF:RF$. Hence it follows that the distances moved by the effort and resistance are proportional to the lengths of the arms upon which they act. In all frictionless machines:

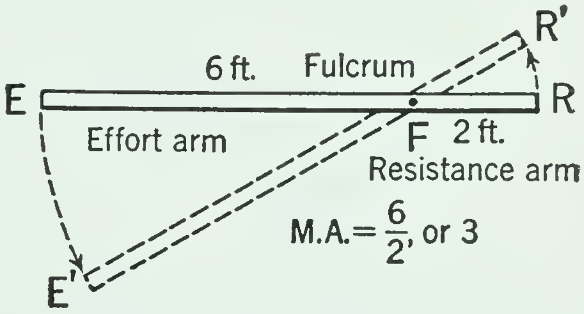


Fig. 4–9. Mechanical advantage of the lever.

$$MA = \frac{De}{Dr} = \frac{R}{E}$$

In all kinds of levers:

$$MA = \frac{EF}{RF}$$

or the length of the effort arm divided by the length of the resistance arm. If EF is 6 ft. long, and RF is only 2 ft. long, then the mechanical advantage is 3.

3. LAWS OF MACHINES APPLIED TO THE LEVER

The efficiency of a lever. Now, having studied the three classes of levers, you can see that the weight of a lever produces a resistance or weight moment in levers of the second and third class. In the case of uniform first-class levers, if the effort distance exceeds the weight distance, the weight of the lever produces an effort moment which really aids the effort; if the fulcrum is in the center of the lever, the weight of each arm counterbalances the other. There is usually a relatively small amount of friction in the use of any simple lever, and for that reason its own weight is the principal factor affecting its efficiency.

$$\text{Efficiency of a lever} = \frac{\text{work output}}{\text{work input}} = \frac{Dr \times R}{De \times E}$$

What is the moment of a force? Before we can understand how a load is distributed between two parallel forces, we need to understand the *moment of a force* or *torque*. Suppose that we have a rigid bar, *AB*, upon the ends of which two parallel forces, *F* and *F′*, are acting. (See Fig. 4–10.) The bar is free to turn about a fixed point, *C*, which is called the *center of moments*. The force *F* is really attempting to turn the bar *AB* about *C* in a clockwise direction, but the force *F′* tends to pull the bar around *C* in a counterclockwise direction. How *effective* is each force? It can be shown by experiment that the effectiveness of any force in producing rotation, or the *moment of the force*, depends upon two things: (1) *The magnitude of the force;* (2) *The length of the arm upon which it acts.* Hence, *the moment of a force is equal to the product of the force times the length of the arm upon which it acts.* For example, a force *F* of 20 lb., acting upon

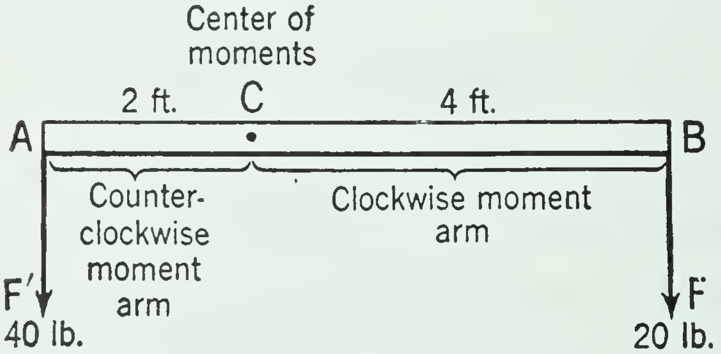


Fig. 4–10. Parallel forces.

the arm 4 ft. long, has a clockwise moment of 80. The force F' of 40 lb. acting upon the arm 2 ft. long has a counterclockwise moment of 80.

If the force F is not applied perpendicularly to the bar AB, as shown in Figure 4–11, then the length of the arm upon which the force acts is not CB, but it is equal to the perpendicular distance d from the line of direction of the force to the center of moments. The moment in such a case is equal to the product of the force F times the distance d.

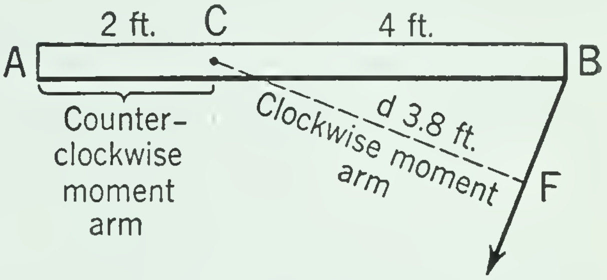


FIG. 4–11. The force acts at an acute angle.

How can one find the center of gravity? If we suspend a weight by means of a small cord, the line along which it will come to rest will, if produced downward, pass through the center of gravity of the earth. Such a weight and cord form a plumb line. If we wish to find experimentally the center of gravity of an irregular object, such as is shown in Figure 4–12, we first suspend it from the point P in such a manner that it may turn freely about the point of suspension. The object will swing about this point and come to rest with its center of gravity directly below the point of support. Now if we drop a plumb line from the same point of support, the center of gravity of the object will coincide with some point in the plumb line.

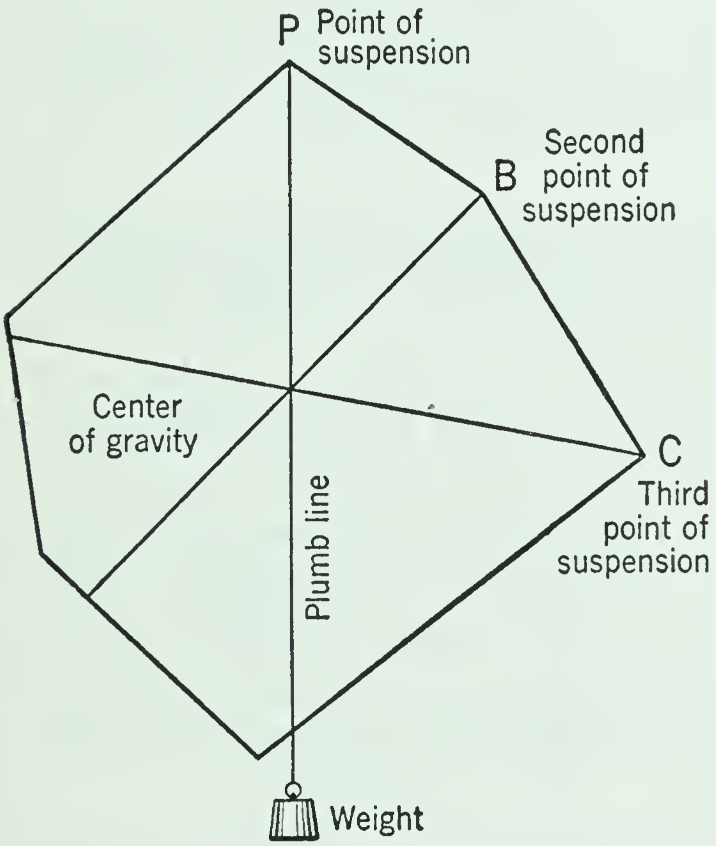


FIG. 4–12. How to find center of gravity experimentally.

A line drawn along the plumb line must pass through this point. Next let us suspend the object from the point B and again draw a line in the direction indicated by the plumb line. For verification, we may repeat the operation, this time suspending the object from the point C. Each of these lines passes through the center of gravity. Therefore the center of gravity of the object lies at the point of intersection of these lines. In your work in mechanics, you will find it very convenient to consider that *an object behaves as if all its weight were concentrated at its center of gravity.*

Demonstration. How can the determination of the center of gravity affect the balance of an object? In an irregularly shaped piece of cardboard about two feet in diameter, punch a small hole near one edge and insert a nail. Attach a string to the nail with a weight on the other end. (See Fig. 4–12.) Draw a line on the cardboard corresponding to the plumb line. Repeat for two or three other positions of the nail in the cardboard. At the point of intersections of these lines punch a hole with the nail and try spinning the cardboard on the nail. Try spinning the cardboard about some other point chosen at random. Compare the smoothness of spinning in the two cases. The point about which the board rotates smoothly is called what?

Center of gravity of a lever. As you have seen, the center of gravity of an object is that point at which all its weight seems to be concentrated. The center of gravity of any uniform lever is in the center of the lever. When any unloaded lever is balanced, the fulcrum has to be at or directly beneath the center of gravity. Balancing a lever, then, enables us to find its center of gravity.

If its center of gravity is not directly over the fulcrum, then the weight of the lever produces a moment of force which is equal to the weight of the lever times the distance from the fulcrum to the center of gravity. This moment must be balanced by an equivalent moment on the opposite side of the fulcrum if equilibrium is actually to be secured.

Demonstration. Find the weight of an object from the known weight of a stick or pole and the position of its center of gravity. Weigh a stick which is about five feet in length and then balance it on a fulcrum. The point of balance should be marked and labeled *C. of G.* Attach the object whose weight is to be determined near one end of the stick. Slide the stick back and forth on the fulcrum until a point is found between the weight and the *C. of G.* where there is equilibrium. Measure the distance from the fulcrum to the *C. of G.* and label it *De*. Measure the distance from the fulcrum to the weight and label it *Dr*. Using the principle of moments, moments clockwise equal moments counterclockwise, as expressed in the following equation, calculate the unknown weight *W*.

$$W \times Dr = \text{Weight of lever} \times De$$

How is a lever affected by its own weight? In the preceding discussion of the lever, we neglected its weight. In practice, the weight of the lever must be considered. We must keep in mind that the lever *acts as if all its weight were concentrated at its center of gravity.*

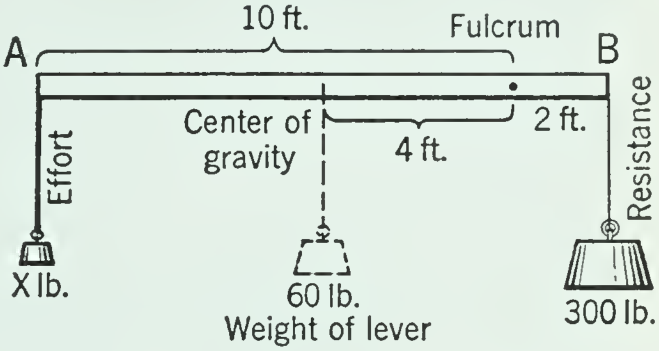


FIG. 4–13. The weight of this lever acts as a counterclockwise moment and aids the effort.

In Figure 4–13, the uniform bar *AB* is 12 ft. long; its weight is 60 lb. At *B*, 2 ft. from the fulcrum, there is a resistance of 300 lb. What effort at *A* is needed to produce equilibrium? The resistance *moment*, or total force, equals 2 × 300, or 600. It acts clockwise. The effort moment equals $10 \times x$, or $10x$; its direction is counterclockwise. But the weight of the lever, 60 lb., acting at its center of gravity, 4 ft. from the fulcrum, is really producing a counterclockwise moment and helping the effort. The sum of the two counterclockwise moments is $10x + (4 \times 60)$. This sum equals the clockwise moment, 600. From the equation, $10x + 240 = 600$, we find that $x = 36$ lb., the effort needed at *A*.

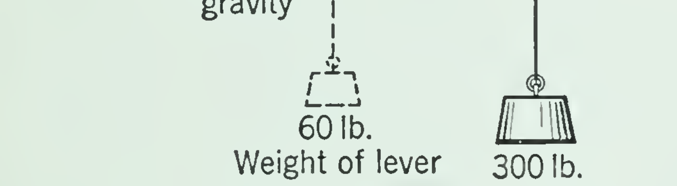


FIG. 4–14. The weight of this lever hinders the effort.

In Figure 4–14 the weight of the lever hinders the effort, since it acts in a counterclockwise direction, the same as the resistance. The lever EF has the fulcrum at the end F, and the effort is applied at the other end E. The lever, which is 12 ft. long, weighs 60 lb. A resistance of 300 lb. is applied at R, 2 ft. from the fulcrum. We wish to find the effort needed at E to secure equilibrium. The resistance moment, 2×300, or 600, and the weight moment, 6×60, or 360, are both acting in a counterclockwise direction. Their sum is 960. The effort moment, $12 \times x$, or $12x$, acts clockwise. Therefore $12x = 960$, and $x = 80$ lb., the effort needed at E. *A lever acts as if all its weight were concentrated at its center of gravity; its weight-moment equals its weight multiplied by the distance from the center of gravity to the fulcrum.*

DEMONSTRATION. How can levers help us to work more effectively?

1. Balance a meter stick on a fulcrum. (See Fig. 4–1.) By means of a string suspend a 1000-gram weight 20 cm. from the fulcrum. On the other side of the fulcrum suspend a 500-gram weight at a point where the stick balances. Place two rulers in a vertical position back of each weight. Move the 500-gm. weight downward 10 cm. How far does the 1000-gm. weight move upward? If the 1000-gm. weight is considered the resistance and the 500-gm. weight the effort, is the advantage here one of speed or of effort? What class of lever does this represent?

2. Place the fulcrum near one end of the meter stick and, by means of a loop of string attachment, hold the other end with a spring balance. (See Fig. 4–5.) Note the balance reading. This reading is due to the weight of the stick. Hang a 500-gm. weight between the balance and the fulcrum. Again read the balance and subtract the first reading from it. The remainder represents the effort necessary to lift the 500-gm. weight. How does the effort compare with the weight? When the effort is moved upward which moves faster, the effort or the weight? Does this represent an advantage of speed or effort? What class of lever does this represent?

3. Attach one end of the meter stick to the water faucet or some other support on the demonstration table. This represents the fulcrum. (See Fig. 4–8.) Pull up with the balance placed about the middle of the stick and note the balance reading. This effort is used to overcome the weight of the stick. Hang a 200-gm. weight near the other end of the stick. Again note the balance reading and subtract the first reading from it. The remainder represents the effort needed to lift the 200-gm. weight. How does the effort compare with the weight? When the effort is moved

upward which moves faster, the effort or the weight? Does this represent an advantage of speed or effort? What class of lever does this represent? What class of lever is the lower part of the recoil mechanism of the 155-mm. gun shown in Figure 4–15?

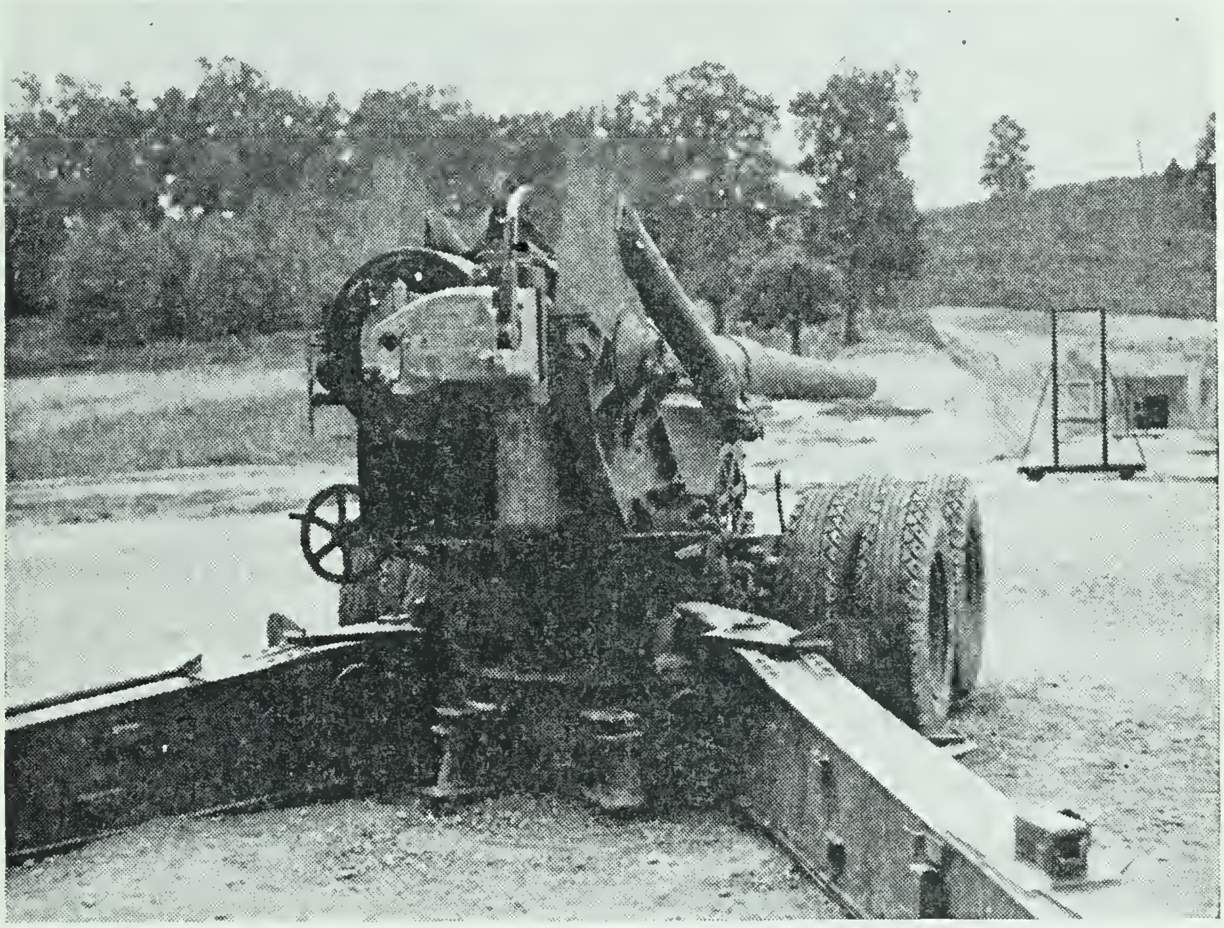


Photo by U.S. Army Signal Corps

FIG. 4–15. A 155-mm. gun ready to fire its projectile into a 450-foot tunnel in a test. Note the simple lever and the pneumatic piston in the recoil mechanism.

How is equilibrium secured? A book lying on a table pushes down upon the table with a force equal to its weight. The table must push upward with an equal force if the book remains in equilibrium. In order to keep the book or any other object in equilibrium, there must be no *unbalanced* force acting upon it. A push from one side must be balanced by an equal push from the opposite side. *An object is said to be in equilibrium when no unbalanced force acts upon it.* In other words, *the resultant of all the forces acting upon it is zero.*

To secure equilibrium, two kinds of motion must be prevented: *translatory*, or motion along a line; and *rotary*, or motion about a point acting as a pivot. Suppose that we have two parallel forces, *D* and *E*, of 80 and 120 lb. respectively, acting upon a bar at points *A* and *B*. (See Fig. 4–16.) A force of 200 lb. applied in the opposite direction at *O* will prevent translatory motion, but it will not prevent rotary motion. Disregarding the weight of the lever, rotary motion may be prevented if the force of 200 lb. is applied at the center of moments, *X*. (See Fig. 4–17.) Suppose the bar is 20 ft. long; then the equilibrant must be applied at a point 8 ft. from *B*, the greater force. The lengths of the arms upon which the two forces act are inversely proportional to the magnitude of the forces.

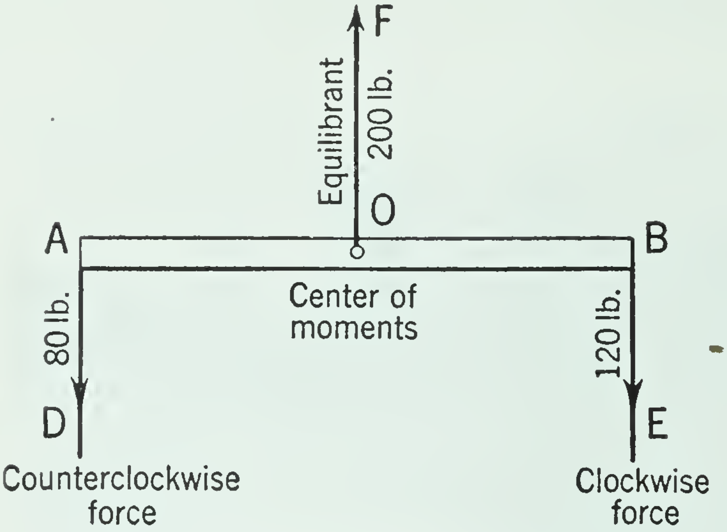


FIG. 4–16. The force at *F* prevents translatory motion.

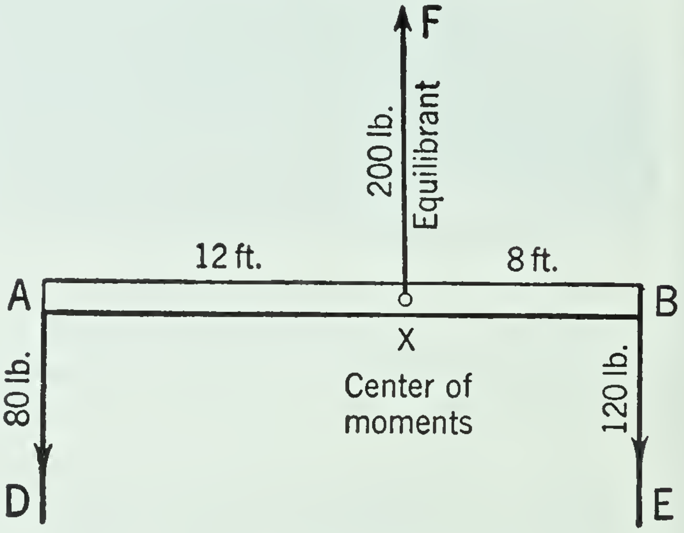


FIG. 4–17. The force at *X* produces equilibrium.

PROBLEM. A bar 30 ft. long is pivoted so that it is free to rotate about the point *C*. (See Fig. 4–18.) At *A*, 6 ft. from *C*, a force of 400 lb. acts downward; at *B*, 24 ft. from *C*, a force of 50 lb. acts downward; at *D*, 10 ft. from *C*, there is a downward force of 100 lb.; at *E*, 4 ft. from *B*, a force of 80 lb. acts upward; and at *F*, 2 ft. from *A*, a force of 250 lb. acts upward. Neglecting the weight of the bar, where must a force of 200 lb. be placed to secure equilibrium, and in what direction must it act?

Solution. The forces *B*, *D*, and *F* act clockwise; their distances from *C* (all distances must be measured from the center of moments) are 24, 10, and 4 ft. respectively. The forces *A* and *E* act counterclockwise; their distances from *C* are 6 and 20 ft. respectively. We solve the problem by finding the difference between the sums of the clockwise and counterclockwise moments. Then we may let x equal the distance that a 200-lb. force must be placed from *C* to produce equilibrium. Its moment, $200x$, must equal the difference.

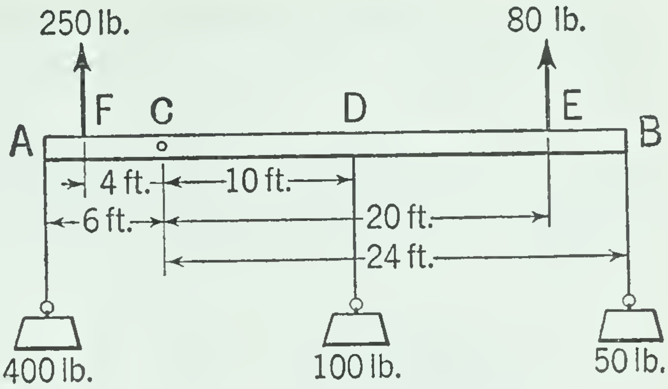


FIG. 4–18. The bar is in equilibrium when the algebraic sum of all the moments is zero.

Clockwise moments

$$\begin{aligned} 24 \times 50 &= 1200 \\ 10 \times 100 &= 1000 \\ 4 \times 250 &= \underline{1000} \\ \text{sum} &= 3200 \end{aligned}$$

Counterclockwise moments

$$\begin{aligned} 6 \times 400 &= 2400 \\ 20 \times 80 &= \underline{1600} \\ \text{sum} &= 4000 \\ &\ \underline{3200} \\ \text{difference} &= 800 \end{aligned}$$

Since $200x = 800$, then $x = 4$ ft., the distance from *C* the 200-lb. force must be placed. Since the counterclockwise forces are greater, it must be used as a clockwise force. Hence, it may act downward 4 ft. to the right of *C*, or upward 4 ft. to the left of *C*.

Any number of parallel forces are in equilibrium if the sums of the opposite forces are equal, and the sum of all the clockwise moments is equal to the sum of all the counterclockwise moments.

DEMONSTRATION. How do the clockwise moments compare with the counterclockwise moments when a lever is in equilibrium? Balance a meter stick on a fulcrum. Hang a 500-gm. weight 18 cm. from the fulcrum and balance it with a 200-gm. weight on the other side of the fulcrum. When the equilibrium point has been found note the distance from the 200-gm. weight to the fulcrum. Compute the clockwise moment and the counterclockwise moment and compare the two.

When is a body in stable equilibrium? If an object is in stable equilibrium, it cannot be overturned without first raising its center of gravity. If slightly tipped, the object tends to return to its former position. The bricks shown in Figure 4–19 are both in stable equilibrium, but their degree of stability differs. To overturn block (*A*) about the edge *P*, the center of gravity *C* must be raised to the point *B*. When the center of gravity passes beyond the vertical line from *A*, so that it falls outside the area included within the base, the brick will be overturned and fall to the position shown by the dotted lines. The same brick, standing on end, position (*B*), is also in stable equilibrium, but it is not so hard to overturn it as when it lies flat on its side. In position (*A*) the center of gravity must be lifted the vertical distance *BA* before it can be overturned; in the position shown in Figure 4–19 (*B*) the center of gravity must be lifted from *D* to *E* before it can be overturned. *BA* is much greater than *ED*; hence the greater stability when the block lies on its side. *The stability of an object may be increased by enlarging the base and by having the center of gravity as low as possible.*

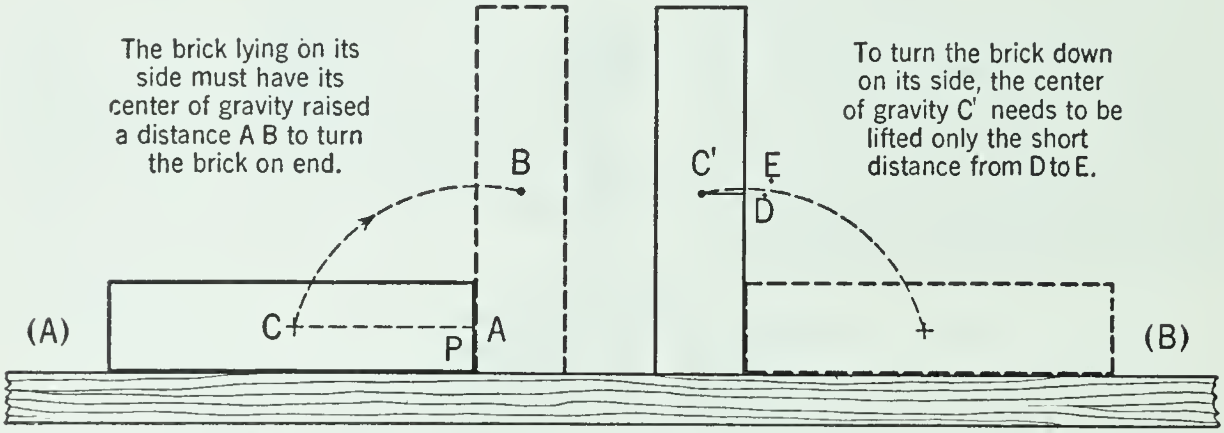

The brick lying on its side must have its center of gravity raised a distance A B to turn the brick on end.
B
C'
E
D
To turn the brick down on its side, the center of gravity C' needs to be lifted only the short distance from D to E.
(A)
C
P
A
(B)

FIG. 4–19. To stabilize an object we may broaden its base or lower its center of gravity.

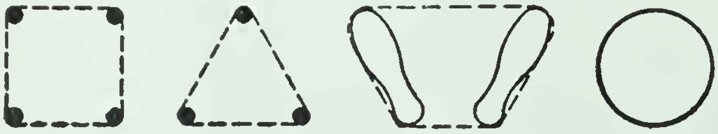


FIG. 4–20. Base of support.

The base of support is represented roughly by the area enclosed by the perimeter drawn around the supporting members. The dotted lines of Figure 4–20 enclose the area of the base. With a three-legged stool the base is triangular; with an ordinary chair it is a rectangle.

A boat loaded with freight sinks very low in the water; at the same time the center of gravity is lowered, increasing its stability. A load of stone is less likely to be upset than one of hay, since the center of gravity of a load of stone is lower. In Figure 4–21 the loaded truck on the sloping road will upset when the load is high enough to have its center of gravity at C'. A plumb line let fall from C' falls outside the wheel base. If the top of the load is removed, the center of gravity is made lower. A plumb line let fall from C falls within the area described by the wheel base, and the load is stable.

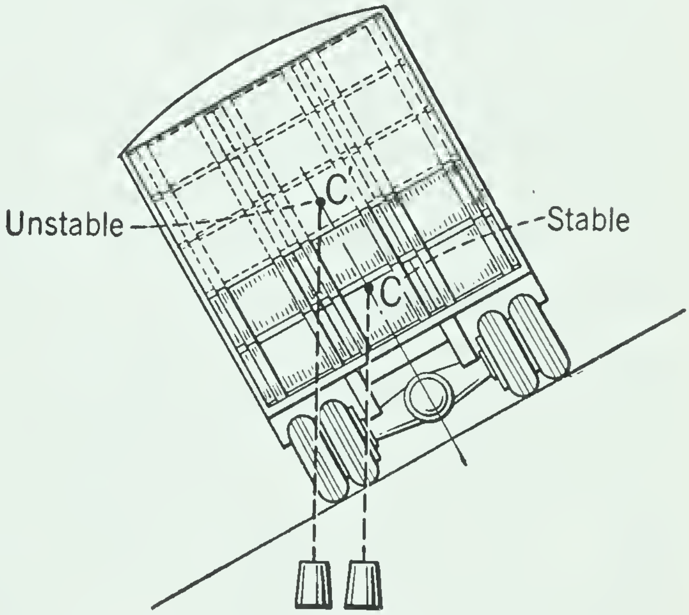


Fig. 4–21. The truck is stable when plumb line dropped from center of gravity falls within area between the wheels.

Automobiles are now built close to the ground so that the center of gravity is as low as possible, thus insuring greater stability. The linemen on a football team at the beginning of each play increase their stability by spreading their feet apart and keeping their bodies low.

When is a body in unstable equilibrium? An egg standing on its end is in unstable equilibrium. A person walking a tightrope is another example. As soon as the slightest displacement occurs in either case, the center of gravity falls outside a plumb line perpendicular to the point of support; it begins to be lowered at once, and the object falls. In unstable equilibrium, the center of gravity is directly above the point of support. The point of support is a sharp point, or a sharp edge, or a curved surface, so that in either case the area of the supporting base is a very small quantity.

What is neutral equilibrium? A ball lying on a table is in neutral equilibrium. A cylinder or a cone lying on its side, and a wheel free to turn upon its axle, are other examples of neutral equilibrium. Such objects come to rest in any position since the center of gravity is neither raised nor lowered when the object is overturned. (See Fig. 4–22.)

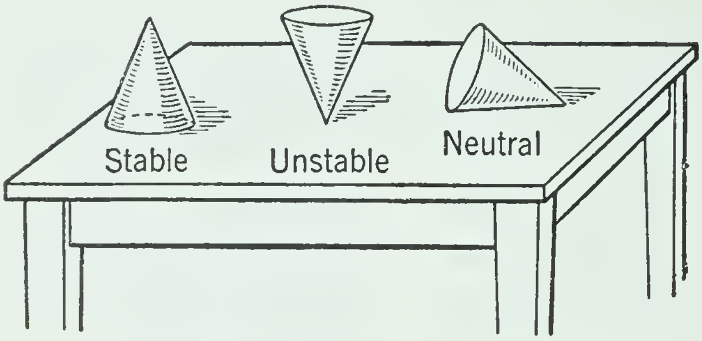


Fig. 4–22. Types of equilibrium.

Demonstrations. Using a wooden cane, show the meaning of stable, unstable, and neutral equilibrium.

Using a rectangular piece of wood standing on end, show that if the center of gravity is pushed outside the base the block will overturn.

What are parallel forces? If two men carry a load on a stick between them, both are pulling in the same direction upon the stick, and the two forces are parallel to each other. They do not have the same point of application. Of course *the resultant of two parallel forces is equal to their sum,* if their direction is the same. Two horses pulling a loaded wagon furnish another example of parallel forces. The piers, or abutments, of a bridge both push up on opposite ends of the bridge, furnishing us with another example of parallel forces.

How can we find the equilibrant of two parallel forces? To produce the same effect as two parallel forces, a single force or *resultant* must be equal to the sum of the forces. It must act in the *same* direction and it must be *applied at the center of moments.*

It follows, then, that the *equilibrant* of two parallel forces must also be equal to their *sum;* it must be *applied at the center of moments;* and it must act in the *opposite* direction to the resultant. Then the algebraic sum of the equilibrant and the resultant is *zero.* Of course the algebraic sum of the clockwise and counterclockwise moments is also *zero.*

If the two parallel forces act in an opposite direction, then they tend to produce rotation. They are acting as a *couple.* In such a case, it is impossible to find any single force which will act as an equilibrant and produce equilibrium. Two hands applied to a steering wheel furnish an example.

In all types of machines we have to deal with several kinds of force. In the first place, there is always an *acting force,* or *effort,* which is so applied to the machine that it attempts to produce motion. In the second place, there is always a *resisting force,* or *resistance,* which represents the load to be lifted or moved. Friction and weight of parts represent the other forces.

How do we use the principle of moments? If two horses are pulling a loaded wagon and the hole in the doubletrees or evener upon which they pull is bored in the middle, then each horse must pull with the same force to move the load. If one horse is much stronger than the other, we make him pull more than 50% of the load by boring the hole in the doubletrees an inch or two from the center, and hitching the stronger horse to the shorter end of the doubletrees.

Two boys carry a load on a stick between them. (See Fig. 4–23.) The stick is 8 ft. long. The load, which weighs 160 lb., is placed 3 ft. from the boy at *A*, and 5 ft. from the boy at *B*. Let us inquire what part of the load each boy carries. To find the upward force the boy at *A* must use, let us consider that the hand of the boy at *B* acts as a center of moments. *A* is pulling upward (clockwise) upon an arm 8 ft. long. Let x equal the force he exerts. Then the clockwise moment equals $8x$. But the load *W* is pulling downward (counterclockwise) with a force of 160 lb. upon an arm 5 ft. long. Its moment is 5×160, or 800. If the bar is in equilibrium, the two moments are equal. Then $8x = 800$. And x, the force at *A*, is 100 lb. To find the force needed by the boy at *B*, we assume that the center of moments is at *A*. Then the upward force x at *B* acts counterclock-

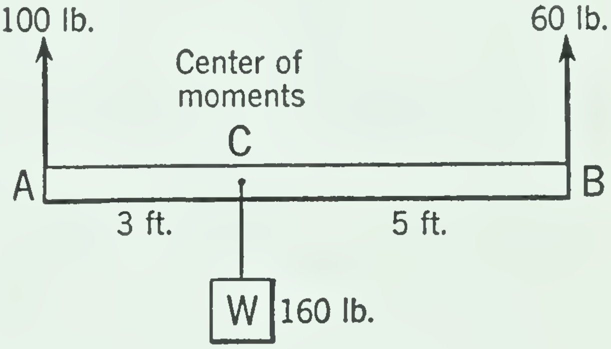


FIG. 4–23. How a load is apportioned between parallel forces.

wise upon an arm 8 ft. long. The load, 160 lb., acts clockwise upon a 3 ft. arm. The moments are $8x$ and 480 respectively. Since $8x = 480$, then $x = 60$, the force at B. In these cases the weight of the stick was not considered.

The ends of a bridge pushing down upon the piers or abutments furnish another example of parallel forces. The force acting downward upon each pier is the same as the force needed to lift the end of the bridge at that pier. Suppose that the bridge AB is 100 ft. long and that a weight of 10,000 lb. rests on the bridge 30 ft. from A. (See Fig. 4–24.) Suppose we neglect the weight of the bridge. The clockwise moment at A equals $100x$; the counterclockwise moment of the weight on the bridge is $70 \times 10{,}000$, or 700,000. But these moments are equal. Hence, $100x = 700{,}000$, and $x = 7000$ lb. The number of pounds supported by pier B is found in a similar manner. Using A as the center of moments, we find that $100x = 30 \times 10{,}000$. Therefore $x = 3000$ lb. If the weight of the bridge is distributed uniformly along its length, then each pier will support an additional weight equal to half the weight of the bridge. This force always acts upon the piers of the bridge.

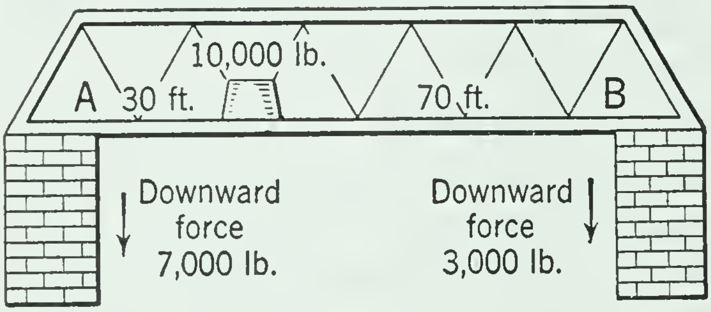


FIG. 4–24. Parallel piers support the bridge.

B. THE PULLEY

1. KINDS OF PULLEY SYSTEMS

What is a pulley? The simple machine known as the *pulley* consists of a wheel, usually grooved, so mounted in a frame or block that it may turn readily upon a fixed axis. The frame may be made of metal or of wood. Two or more wheels may be mounted in the same frame, either on the same axis, as in Figure 4–25, or on different axes, as in Figure 4–26. When two or more wheels are mounted in the same block, the pulley is said to have two or more *sheaves.* For the sake of clearness, we shall use pulleys of the type shown in Figure 4–26 in diagrams, although those of the type shown in Figure 4–25 are more often used in actual practice.

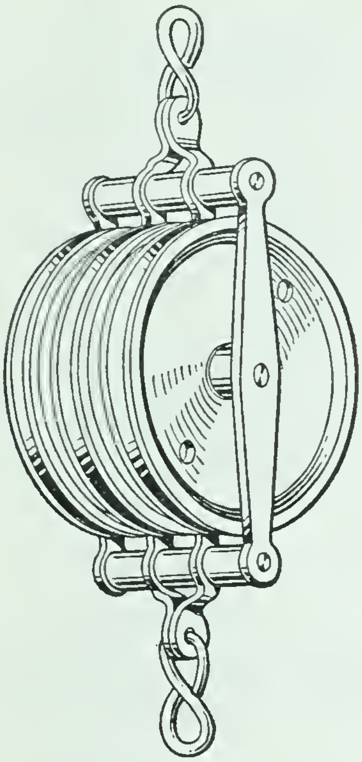


Fig. 4–25. Pulley, with three sheaves, all on the same axle. A common type.

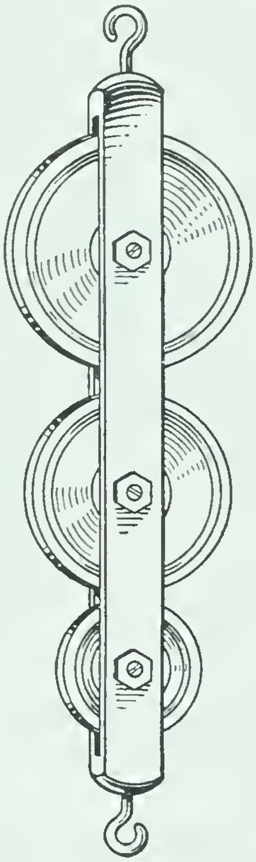


Fig. 4–26. Pulley, with three sheaves. They have different axles.

2. HOW TO DETERMINE THE MA OF A PULLEY SYSTEM

For what is a single fixed pulley used? A single fixed pulley is really a lever of the first class. The arms *EF* and *RF*, Figure 4–27, are equal; hence the mechanical advantage is one. When 1 lb. pulls downward at *A* through a distance of 1 ft., a resistance of 1 lb. at *B* is raised 1 ft. A single fixed pulley gains neither force nor speed; its purpose is to change the direction in which a force is applied.

For what is a single movable pulley used? The single movable pulley is really a lever of the second class. In Figure 4–28, the effort *E* acts upon the arm *EF*, which is the diameter of the pulley. The resistance *R* acts upon the arm *RF*, which is the radius of the pulley. Since the diameter is twice the radius, the mechanical advantage of the single movable pulley is two. When the effort at *A* moves 2 ft., the resistance at *B* is lifted 1 ft. If we fasten both ends of the cord, it is evident that each point of support bears one-half the weight.

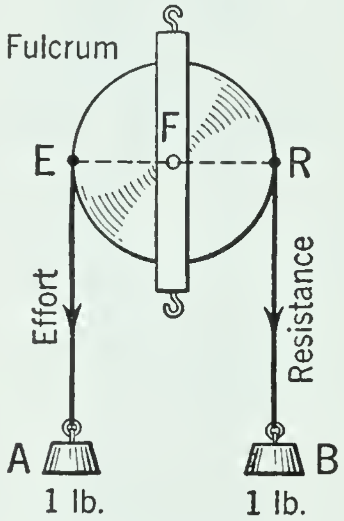


Fig. 4–27. Single fixed pulley. Mechanical advantage is one.

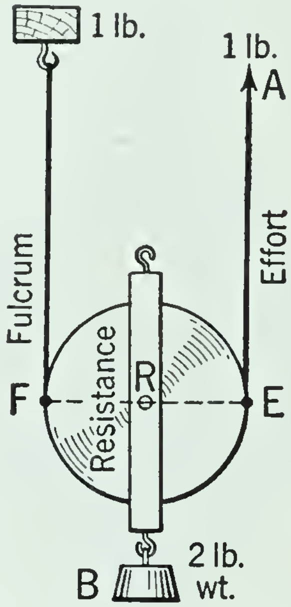


Fig. 4–28. Single movable pulley. Mechanical advantage is two.

How are pulleys combined? It is possible to have many different combinations of fixed and movable pulleys. (See Fig. 4–31.) We shall consider two cases, in both of which the cord or rope is continuous. Of course the effort is applied at one end of the cord, and the other end may be attached (1) to the movable block or (2) to the fixed block.

(1) *To the movable block.* Let us refer to Figure 4–29. One end of the cord is attached to the movable block, passes up over a fixed pulley, down over a movable one, then over a second fixed pulley, and so on. The effort, *E*, must pull downward a distance of 5 ft. to lift the resistance, *R*, a height of 1 ft. Hence the mechanical advantage is 5, *exactly equal to the number of strands supporting the movable block.* The strand of cord to which the effort is attached does not *support* the movable block. It does not increase the mechanical advantage, but merely changes direction.

(2) *To the fixed block.* If we refer to Figure 4–30, we see that one

end of the cord is attached to the fixed block, and that the number of strands supporting the movable block is four. The last strand, to which the effort is attached, merely changes direction. If we let the letter n represent the number of strands supporting the movable block in a pulley system, then the pulley formula becomes:

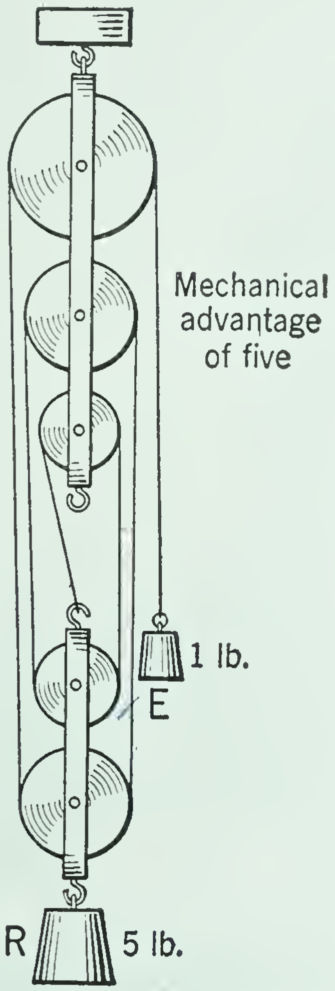


Fig. 4–29. Five strands support the movable block.

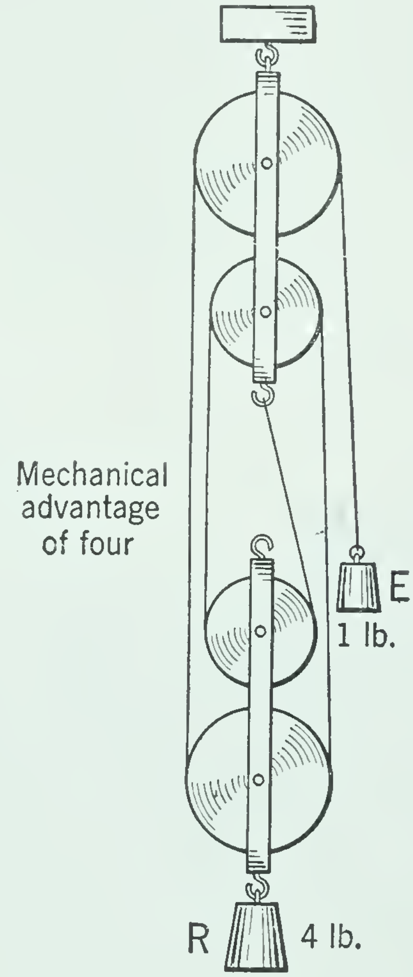
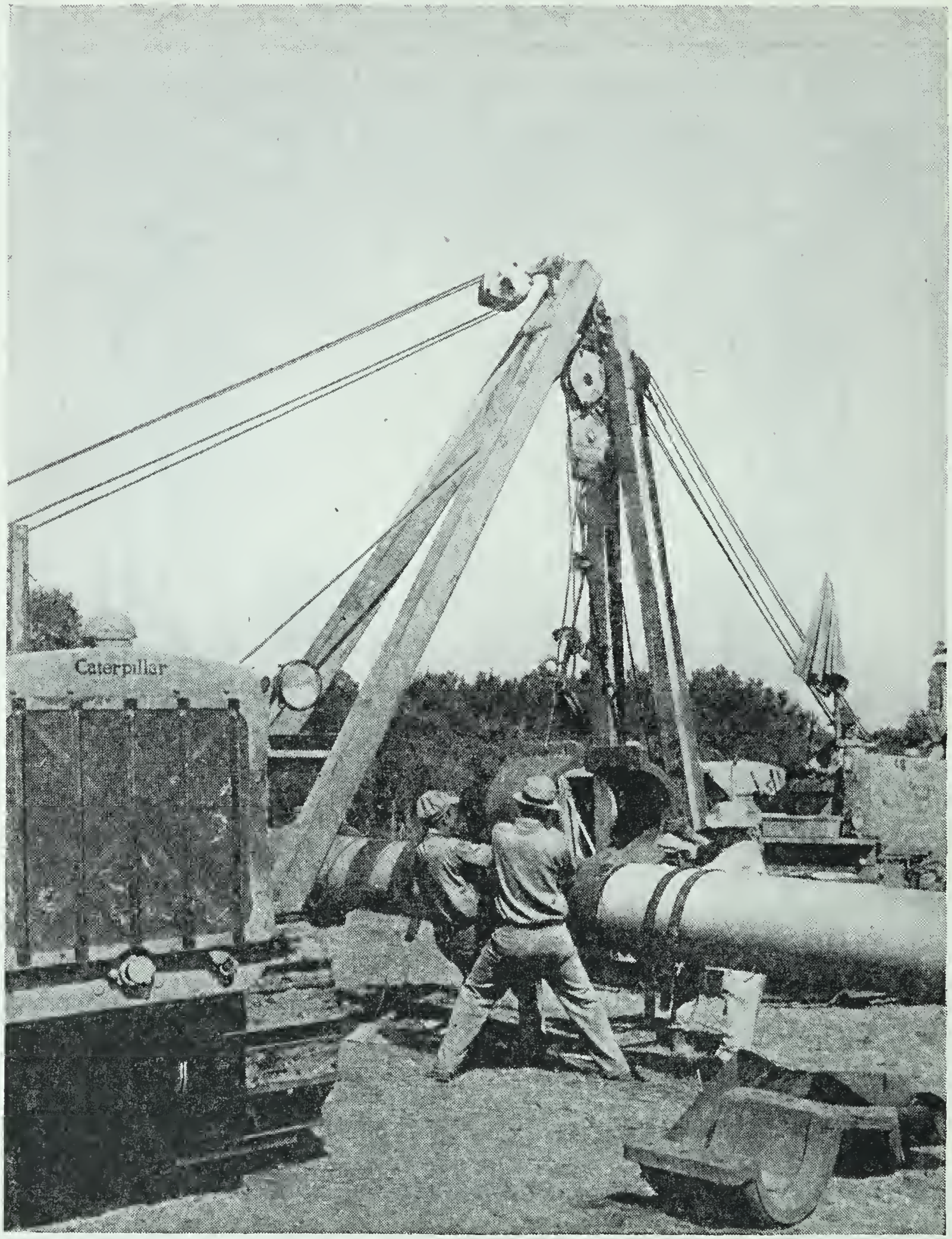


Fig. 4–30. Four strands support the block.

$$En = R$$

It may help the memory if we note that the mechanical advantage is always an odd number when the end of the cord is attached to the *movable* block. It is an *even* number when the end of the cord is attached to the *fixed* block. In the arrangement shown in Figure 4–30, the mechanical advantage is *four.* With the arrangement shown in Figure 4–29, the end of the cord is attached to the movable block.



Philip Gendreau

Fig. 4–31. A huge block and tackle is being used to handle this heavy pipe through which oil will be transported from Texas to Chicago. This photograph was taken near Glenwood, Iowa.

3. THE EFFICIENCY OF THE PULLEY

Friction between cord and sheaves and the weight of the movable block are the main factors which tend to reduce the efficiency of a pulley system. Because of these factors, the law of machines (work input equals work output) as applied to ideal machines, does not hold true because work output is actually less than work input. Likewise the actual MA $\left(MA = \frac{R}{E}\right)$ is less than the ideal MA (MA = number of supporting strands).

4. APPLICATIONS OF PULLEYS

Where are pulleys used? The cords that support our windows pass over fixed pulleys in the window frame. (See Fig. 4–32.) We use a pulley to raise flags, awnings, and some window shades. Men use a combination of ropes and pulleys for putting hay into a mow. The painter uses pulleys to raise or lower the ladders he uses as a platform. An elevator cable passes over a pulley to a drum, upon which the cable is wound as the elevator is lifted. The moving van is equipped with a block and tackle, which is a system of pulleys, for use in lifting heavy pieces of furniture to the upper floors of a dwelling.

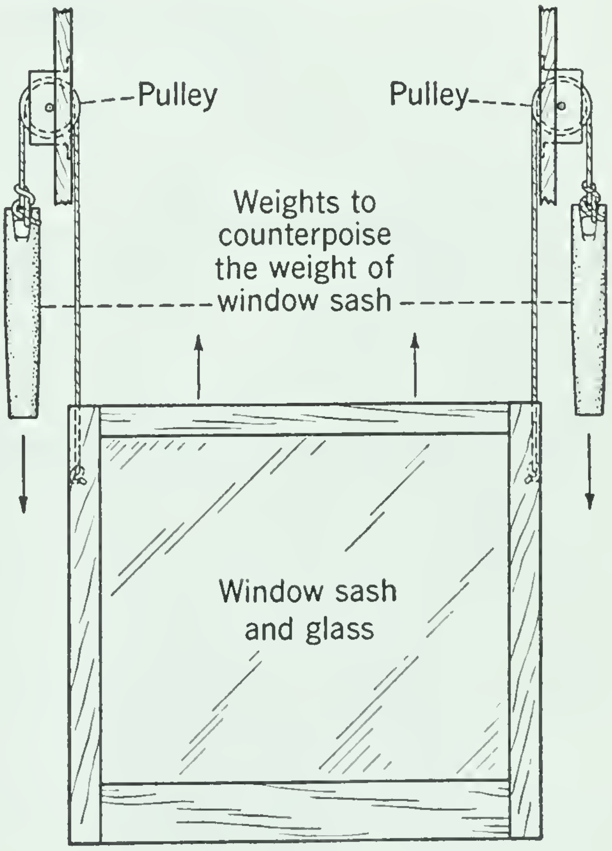


Fig. 4–32. Fixed pulleys are used to change the direction of the force of the weights so that they will lift the window sash. The sum of the weights is slightly less than that of the sash.

Demonstration. How can you determine the MA of a pulley or a system of pulleys?

Set up a single fixed pulley as in Figure 4–27. Attach the pulley to an iron clamp on a ring stand. To one end of the string attach a 1000-gm. weight. Hang weights on the other end of the string until equilibrium is reached. Compare this total force with the 1000-gm. weight. When the weight is moved up 10 cm. how far does the force move down? What class of lever does this pulley represent? What is its *MA*? For what general purpose may it be used?

Repeat the demonstration using a single movable pulley as in Figure 4–28. Attach a spring balance at *A* and note its reading. Next attach a 1000-gm. weight at *B* and note the balance reading. Subtract the first reading from the second. The remainder represents the effort needed to raise the weight. Compare this effort with the 1000-gm. weight. How far does the weight move when the effort moves 10 cm.? What class lever is this pulley? What is its *MA*? Is there a gain in effort or in speed?

Repeat the above demonstrations using various pulley combinations. In each case how does the number of supporting strands compare with the *MA* which you determined?

C. WHEEL AND AXLE

1. HOW TO DETERMINE THE MA OF A WHEEL AND AXLE

A well-known experience with wheel and axle. At some time you probably tried to open a door and found that the door knob had been removed. If you tried to turn the square bolt without the knob, you found it difficult, and gained a greater appreciation of the mechanical advantage given by this common example of the wheel and axle. The effort is applied to the circumference of the knob, and the resisting spring is applied to the circumference of the axle. Since the circumference of the knob is greater than the circumference of the axle, the mechanical advantage is one of force, because *De* is greater than *Dr*.

We notice that the simple machine known as the *wheel and axle* consists of a wheel or crank rigidly attached to the axle which turns with it. You must not confuse it with a wheel turning on an axle, like the front wheel of an automobile, which is *not* an application of this simple machine. The steering wheel of a car is an example, however, because the shaft to which the wheel is attached turns whenever you turn the wheel.

Finding the *MA*. Let us refer to Figure 4–33. We have two wheels of unequal diameter fastened together so that they can turn around the axis, F. In one revolution, the effort, E, travels a distance equal to the circumference, C, of the wheel. In the same time, the resistance, R, will travel a distance equal to the circumference, c, of the axle. Since $De = C$, and $Dr = c$, then the mechanical advantage, MA, of the wheel and axle equals C/c. Instead of the expression

$$MA = \frac{\text{circumference of wheel}}{\text{circumference of axle}}$$

we may use either of the following expressions:

$$MA = \frac{\text{diameter of wheel}}{\text{diameter of axle}}$$

$$MA = \frac{\text{radius of wheel}}{\text{radius of axle}}$$

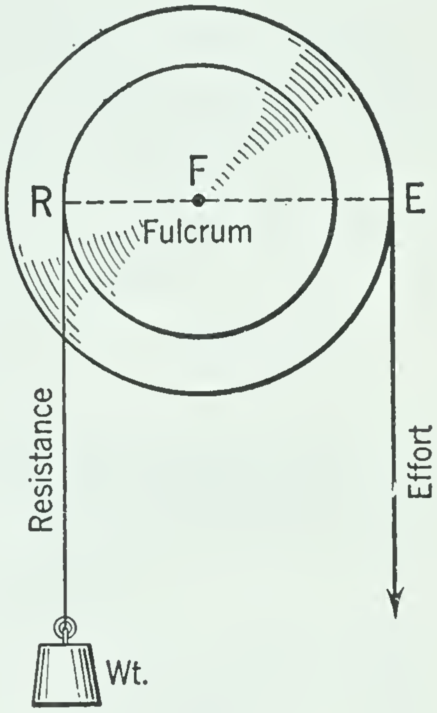


FIG. 4–33. Wheel and axle. Both turn on same shaft, or the same center.

The reason is obvious, for the circumferences of the two wheels are directly proportional to their diameters or to their radii.

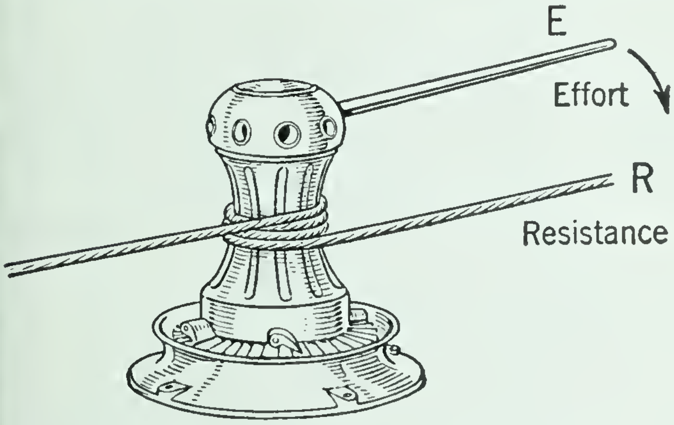


FIG. 4–34. The capstan finds use in hoisting anchors.

PROBLEM. A force of 100 lb. is applied to the rim of a wheel 2 ft. in diameter. What resistance can be counterbalanced upon the axle, which has a diameter of 4 inches?

Solution. The *MA* of this wheel and axle equals

$$\frac{\text{diameter of wheel (24 in.)}}{\text{diameter of axle (4 in.)}}.$$

Since the machine has a mechanical advantage of 6, then 100 lb. of force can counterbalance a resistance of 600 lb.

2. THE EFFICIENCY OF THE WHEEL AND AXLE

Formula for efficiency. Again, the law of machines does not hold true in practical application since the work input, $C \times E$, is, owing to friction, greater than work output, $c \times R$. Similarly, the actual MA $\left(MA = \frac{R}{E}\right)$ is less than the ideal MA:

$$\left(MA = \frac{C}{c} = \frac{D}{d} = \frac{R}{r}\right)$$

The efficiency of the wheel and axle can be determined by using the following equation:

$$\text{Efficiency} = \frac{c \times R}{C \times E} \text{ or } \frac{\text{Actual } MA}{\text{Ideal } MA}$$

3. SOME APPLICATIONS OF WHEEL AND AXLE

Wheel and axle in boats, automobiles, kitchens. The *capstan* used for hoisting the anchor of a ship is an example of the wheel and axle in which the effort is applied at the ends of several levers. (See Fig. 4–34.) The *windlass* used for lifting water from wells is another example of the wheel and axle. As the crank of Figure 4–35 is turned, the rope is wound upon the axle, thus lifting the bucket and contents. The *hoisting derrick* works on the same principle, and also the steering wheels of motorboats and automobiles. In the kitchen, we find the wheel-and-axle principle applied in the meat chopper, the egg beater, the coffee grinder, and the grinding wheel.

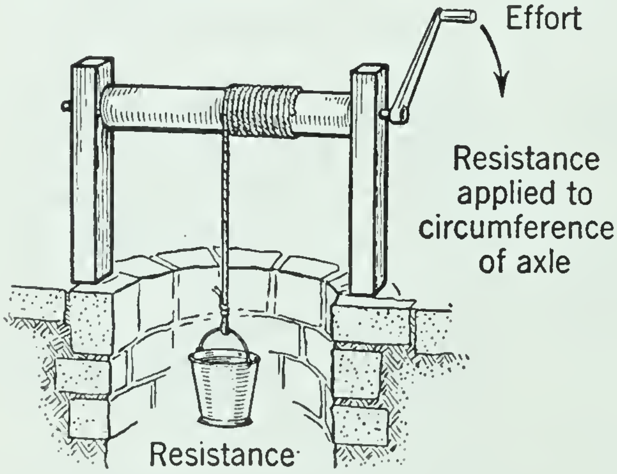


Fig. 4–35. The windlass is used for vertical hoisting.

DEMONSTRATION. Clamp a model wheel and axle to a ring stand. Attach a 200-gm. weight to the axle. (See Fig. 4–33.) Attach weights to the effort string on the wheel until equilibrium is obtained. Compare the weight and the effort. Measure the diameter of the wheel and the diameter of the axle. Find the mechanical advantage, first by dividing the weight by the effort and, second, by dividing the diameter of the wheel by the diameter of the axle. Are these two computations equal? Explain.

D. THE INCLINED PLANE

1. HOW TO DETERMINE THE *MA* OF AN INCLINED PLANE

Formulas for *MA*. We see men wheeling loads up an inclined gangplank, pushing weights up inclined planks to load motor trucks, and building ramps for use in stadiums, or for driving automobiles to the upper floors of garages for parking. In all these cases, it requires less effort to pull or push a resistance up the inclined surface than it does to lift it vertically. Of course, the effort has to travel the whole length of the plane in order to lift a load the height of the plane, if the *force is applied parallel to the plane.* (See Fig. 4–36.) Since *De* is the length *l* of the plane and *Dr* is the height *h*, then:

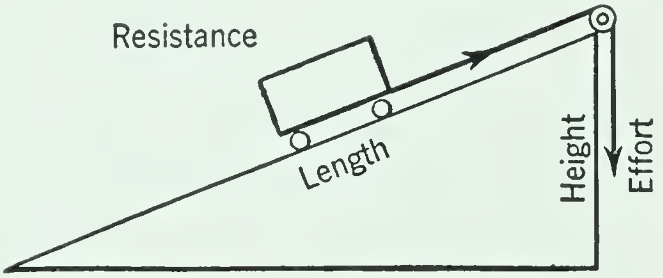


FIG. 4–36. The inclined plane is a much used simple machine.

$$MA = \frac{\text{length of plane}}{\text{height of plane}} \text{ or } \frac{l}{h}$$

Theoretically, 1 lb. of effort will push a weight of 5 lb. up an inclined plane 20 ft. long and 4 ft. high.

Effort : resistance = height : length

PROBLEM. An inclined plane is 18 ft. long and 2 ft. high. What force will be needed to keep a weight of 2000 lb. from sliding down the plane, if we neglect friction?

Solution. $E : R = h : l$. By substitution, $E : 2000 = 2 : 18$. Therefore $E = 222.2$ lb. Or, by analysis, we find that the $MA = \frac{l}{h}$, or 9. When one has a mechanical advantage of 9, it will require $\frac{2000}{9}$, or 222.2 lb. to counterbalance 2000 lb.

A team of horses, pulling a log up inclined skids to a wagon, walk along the ground, and their pull is *parallel to the base of the plane.*

$$MA = \frac{\text{base of plane}}{\text{height of plane}}$$

Other cases may occur where it is inconvenient to apply the effort parallel to the plane; then it must be applied parallel to the base or at some other angle.

How do we calculate grade? We know that the advantage of the inclined plane becomes greater as the slope is made more gentle. Engineers use the term *grade* to express the ratio of the height of an incline to its horizontal length. A hill that rises 5 ft. in 100 ft. of horizontal distance has a grade of 5%; if it rises 3 ft. in 100 ft., its grade is 3%. This is about the maximum grade for a good road; therefore, in mountainous regions the roads often wind about the mountain in a long spiral in order to reduce the grade. A zigzag path, or switchback, is sometimes used by trolley lines. At one point in the Appalachian Mountains, known as Horseshoe Curve, the Pennsylvania Railroad makes a loop, as it winds its way to a higher level.

2. THE EFFICIENCY OF THE INCLINED PLANE

The efficiency of the inclined plane varies inversely as the friction (rolling or sliding) on the surface of the incline. Increased friction decreases the amount of work output for a given amount of work input and also decreases the actual MA of that inclined plane.

3. ANOTHER APPLICATION OF THE INCLINED PLANE—THE WEDGE

What is a wedge? The wedge is really a double inclined plane. Since friction plays so important a part in its use, it is difficult to state any accurate law governing its mechanical advantage. Of course, the longer the wedge in proportion to its thickness, the easier it is to drive the wedge against any resistance; hence its mechanical advantage depends upon the ratio of its length to its thickness. (See Fig. 4–37.)

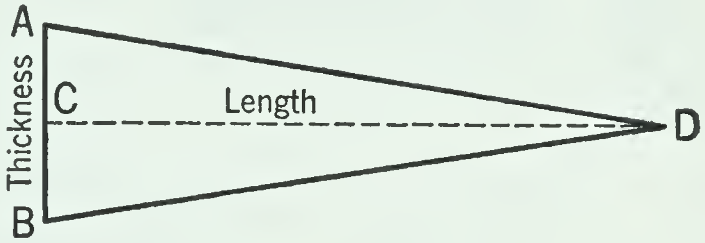


Fig. 4–37. The wedge is a double inclined plane.

The uses to which the wedge is put vary widely. Farmers use the wedge for splitting rails and posts. Nails, pins, and needles all act as wedges when they are pushed or driven through some resisting object. Cutting tools of nearly all kinds are wedges.

Demonstration. By means of a ring stand and iron clamp, or a box, elevate one end of a five-foot board to a height of two feet. (See Fig. 4–36.) Fasten a spring balance to a Hall's car, or any small wagon such as a toy wagon, loaded with weights. Weigh the loaded car. Using the spring balance, pull the car up the incline. Observe the balance reading while pulling. Compare this effort with the weight of the loaded car. Measure the length and height of the incline. Compare the product of weight times the height of the inclined plane with product of effort times the length of the plane. Does work input equal work output? Explain. What is gained in using an inclined plane? How is the wedge an example of the inclined plane?

E. THE SCREW

1. HOW TO DETERMINE *MA* OF THE SCREW

What type of machine is a screw? Let us cut a sheet of paper in the shape of a right triangle and wind it on a pencil as shown in Figure 4–38. This makes it easy to see that the screw is really an *inclined plane wound upon a cylinder.* The distance between the threads is called the *interval* or the *pitch* of the screw.

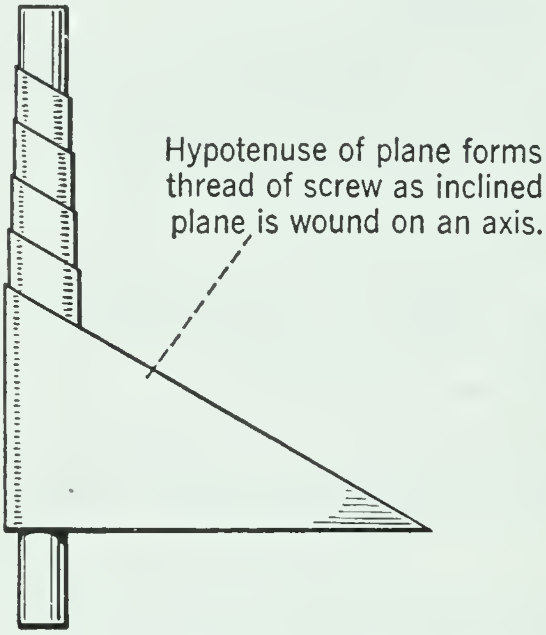

Hypotenuse of plane forms thread of screw as inclined plane is wound on an axis.

FIG. 4–38. The screw is an inclined plane wound on a cylinder.

Formula for *MA*. The effort is often applied at one end of a lever which is set in the head of the screw, although it may be applied to a screw driver set in a groove of the head, or to a wrench which is attached to the head. (See Fig. 4–39.) While the effort describes a complete circle, the head and axis of the screw make one complete turn, and the resistance moves a distance equal to the pitch of the screw.

$$MA = \frac{\text{circumference}}{\text{pitch of screw}}$$

If we let r equal the length of the lever, and d the pitch of the screw, then we have:

$$MA = \frac{2\pi r}{d}$$

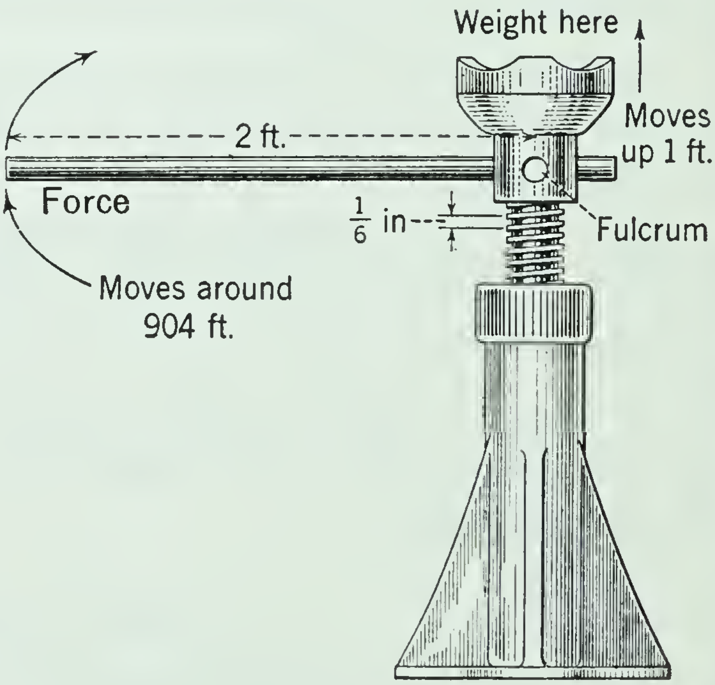


FIG. 4–39. A tremendous gain in force is possible with the use of a jackscrew.

PROBLEM. The lever of a screw is 21 in. long. If the screw has 4 threads to the inch, find the MA of the machine. Neglecting friction, what effort is needed to lift 40,000 lb.?

Solution. $MA = \frac{2\pi r}{d}$, or $\frac{2 \times \frac{22}{7} \times 21}{0.25}$. (Since there are 4 threads to the inch, the pitch is 0.25 in.) $MA = 528$.

To lift 40,000 lb., an effort of $\frac{40{,}000}{528}$, or 75.75 lb., is needed.

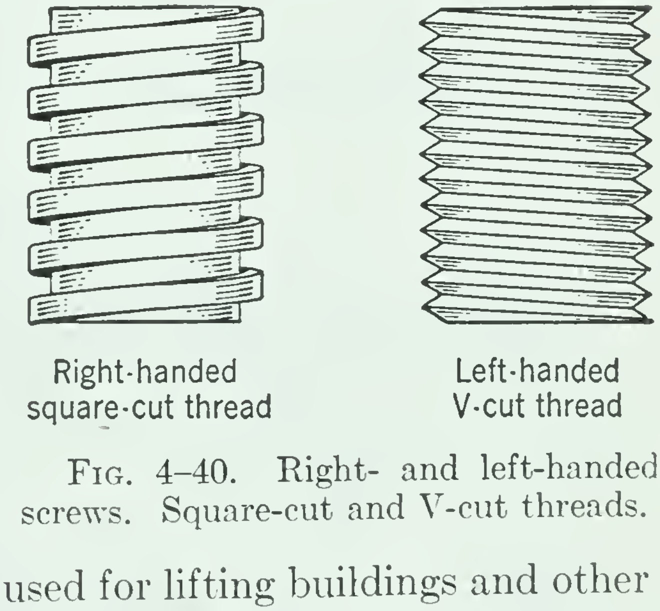
2. THE EFFICIENCY OF THE SCREW

The application of the law of machines and determination of efficiency are the same with respect to the screw or to any other simple machine. The work output ($R \times$ pitch) is less than work input ($E \times$ circumference of effort circle) because of the friction of the screw. For the same reason the actual MA $\left(MA = \frac{R}{E}\right)$ is less than the ideal MA.

$$\left(MA = \frac{\text{circumference}}{\text{pitch}}\right)$$

3. APPLICATIONS OF THE SCREW

What are some uses of the screw? Bolts, nuts, and screws of all kinds are examples of this simple machine. When the threads on a bolt are cut so that the nut must be turned in a clockwise direction as it is tightened, the screw is said to be a right-handed one. When the nut must be turned in a counterclockwise direction to tighten it, the screw or thread is said to be left-handed. (See Fig. 4–40.) The *letter press* and the *vise* are examples of the screw. The *jackscrew*, which is used for lifting buildings and other heavy objects, is a screw having a very high mechanical advantage. For measuring the thickness of paper and foil, or for finding the diameter of wire, a fine-threaded screw may be used. Figure 4–41 shows the *spherometer*. The head of the screw is divided into 50 or 100 parts. If the threads are 1 mm. apart and the head is divided into 100 parts, it is evident that the point of the screw advances only 0.01 mm. when the head is turned from one division to an adjacent one.



Right-handed square-cut thread

Left-handed V-cut thread

Fig. 4–40. Right- and left-handed screws. Square-cut and V-cut threads.

The *micrometer caliper* of Figure 2–8 is used in a similar manner. By its use a skilled mechanic can turn a shaft in a lathe to a required diameter within a few thousandths of an inch. It can be used to find the diameter of hair or wire, or the thickness of a sheet of paper.

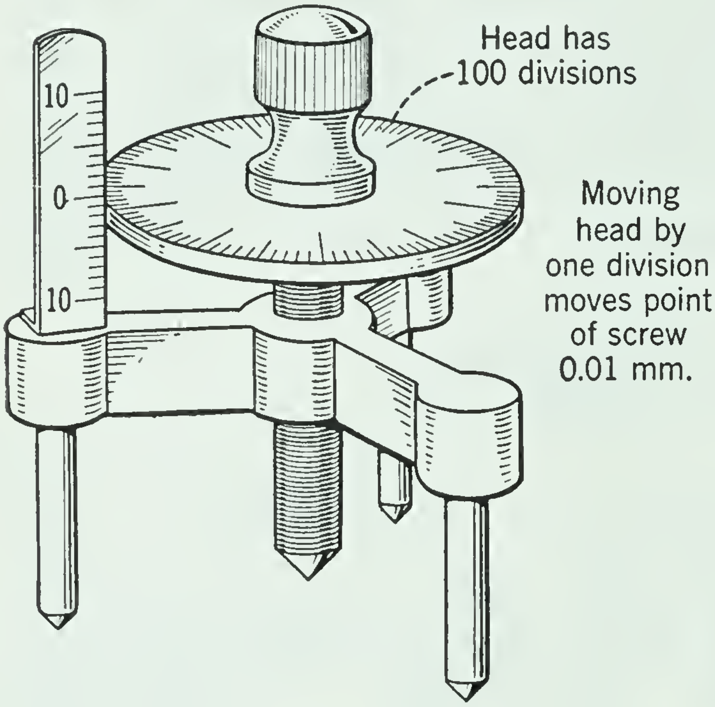


Fig. 4–41. The spherometer is used for accurate measurements.

Demonstration. What is the relation between a screw and an inclined plane? Draw a straight line from corner to corner on a sheet of writing paper. Cut the paper along the edge of the line. Wrap the part containing the line around a dowel so that the line shows. (See Fig. 4–38.) A spiral inclined plane like this is known as what?

F. GEARS

Gears are really compound, not simple, machines. They are treated here for convenience since they are combinations of the wheel and axle or, as in the case of the worm gear, of the wheel and axle and the screw.

1. KINDS OF GEARS

Four common types. One of the several methods of transmitting power is by means of gears. Some of the types of gears are: spur, pinion, bevel, helical, and worm.

The simplest form of toothed wheel or cogwheel is called a *spur gear*. (See Fig. 4–42.)

A *pinion gear* is a spur gear which is in mesh with another cogwheel which has a greater number of teeth or cogs.

If the teeth of a wheel are cut at such an angle as to permit a change in the direction of power transmission, thus causing the two wheels to rotate at an angle, the wheel is called a *bevel gear.*

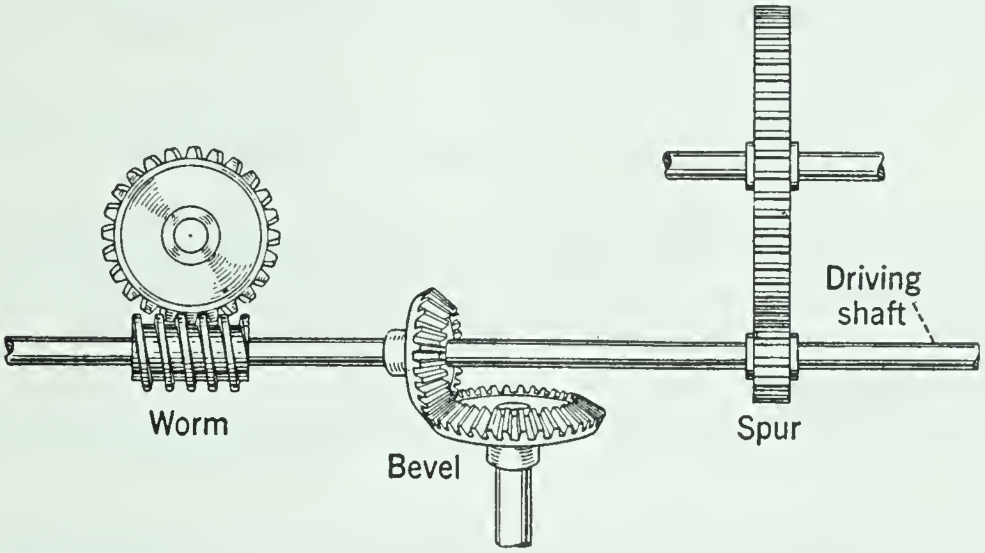


FIG. 4–42. Gears may be used to gain force or speed or to change the direction in which the force acts.

For quiet operation, in such cases as the differential and transmission of a car, the teeth on a cogwheel are in spiral form. The curve of the teeth resembles that of an ordinary screw thread. Such a wheel is known as a *helical gear.*

A combination of a screw and a helical gear is known as a *worm gear.* (See Fig. 4–43.)

Formula for *MA*. In this compound machine, the worm gear, the effort is applied to turn an endless screw, such as the one in Figure 4–43. If there are 50 teeth in the wheel, then one complete turn of the *worm* or endless screw turns the wheel through 1/50 of a revolu-

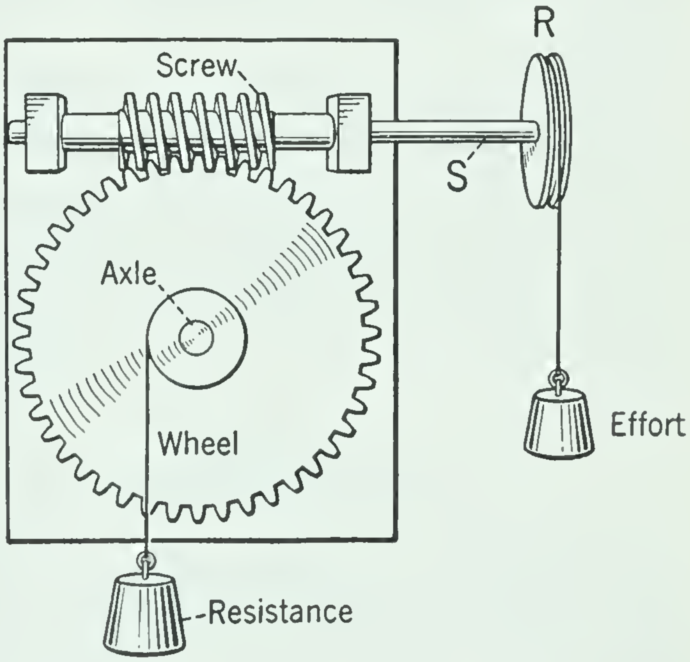


FIG. 4–43. The worm gear has a high mechanical advantage.

tion. The resistance is applied to the axle. If we let l represent the length of the crank lever upon which the effort acts, n the number of teeth in the wheel, and r the radius of the axle, then the mechanical advantage of the worm wheel is equal to $\frac{nl}{r}$.

2. APPLICATIONS OF GEARS

The spur gear, being merely a simple cogwheel, has an almost unlimited number of applications. In the automobile alone, it has many applications, such as the transmission, the timing gear, and the differential.

The pinion gear is found at the differential end of the drive shaft of a car.

The bevel gear also is found applied in the differential of an automobile.

Helical gears may be seen in the differential and the transmission of an automobile.

Worm gears drive some motor trucks and trolley wheels. The worm is turned by the engine or motor and the cogwheel drives the axle.

The steering mechanism of cars, trucks, and tractors utilizes the worm gear. The worm gear is also used to reduce speed rather than for high mechanical advantage. The focusing mechanisms of a microscope, automobile speedometer gear, and speed counters are applications in which the worm gear is sometimes used to reduce speed.

3. GEAR TRAINS—TRANSMISSIONS

Combinations of gears. Any combination of two or more cogwheels may be called a *gear train.* In the transmission of power a gear train may be used to increase speed, decrease speed, or to change the direction of the force.

The *MA* of gear wheels. Let us refer to Fig. 4–44, which shows a train of gear wheels of high mechanical advantage. The effort

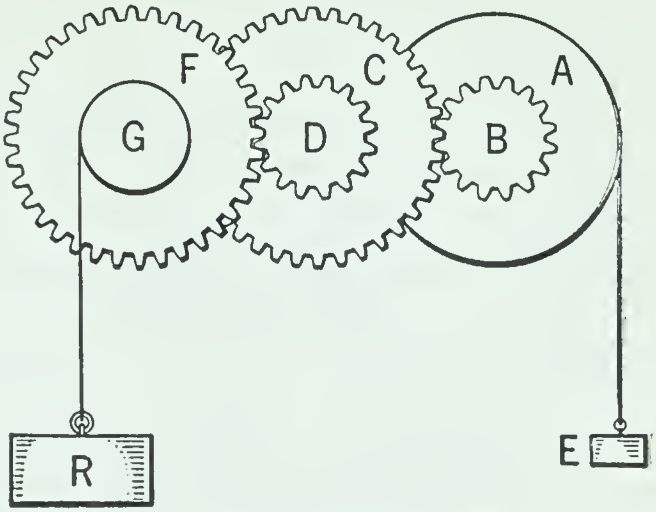


FIG. 4–44. A train of gear wheels used to give mechanical advantage.

is applied at A, which makes one revolution in the same time as its axle B; but wheel C makes only that fraction of a revolution which is equal to:

$$\frac{\text{number of cogs in } B}{\text{number of cogs in } C}$$

The wheel F, too, will revolve only a fraction as rapidly as D. The wheels A and G are essentially wheel and axle. Therefore, the total mechanical advantage equals:

$$\frac{\text{radius of } A}{\text{radius of } G} \times \frac{\text{No. of cogs in } C}{\text{No. of cogs in } B} \times \frac{\text{No. of cogs in } F}{\text{No. of cogs in } D}$$

Gear wheels are much used to vary speed. Suppose a wheel that has 32 gear teeth is in mesh with another wheel that has only 8 teeth, or cogs. If we apply an effort to the first one, we gain speed, since the second one will make four revolutions to one of the first. If we apply the effort to the second wheel, we gain force, and have an MA of 4. In clocks and meters, we use a train of gear wheels for timing or for measuring. In many machines we use gear wheels to vary speed. (See Fig. 4–45.) A *sprocket wheel* is a kind of cogwheel, the cogs or sprockets of which are made to engage with the links of a chain.

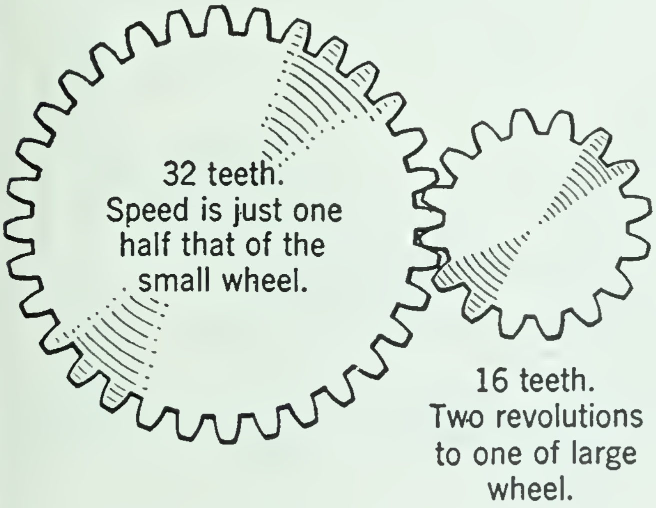

32 teeth.
Speed is just one half that of the small wheel.
16 teeth.
Two revolutions to one of large wheel.

FIG. 4–45. Gears are used to vary speed.

In a bicycle, the sprocket wheels on separate shafts are connected by a chain. In Figure 3–14, the front sprocket wheel has 28 teeth and the rear one only 7. Hence, for one complete revolution of the pedals, the rear wheel of the bicycle will make four complete revolutions.

When an automobile driver shifts gears, he slides one gear wheel backward or forward until it is in mesh with a gear wheel on a countershaft whose speed is controlled by the speed of the crankshaft of the engine. Since the sliding gears and the countershaft gears have different numbers of teeth, the speed can be easily varied.

Demonstration. Make a study of as many kinds of gears as can be made available, such as timing gear, differential, drive shaft, steering mechanism, transmission, and speedometer gear. Classify each gear and determine whether its purpose is to gain speed, or to gain force, or to change the direction of an effort.

G. COMPOUND MACHINES

What is a compound machine? Many complicated-looking machines are found to be combinations of two or more simple machines. A meat chopper has a crank which works on the principle of the wheel and axle as it turns a screw which forces the meat into wedge-shaped knives. In Figure 4–46 we have a safe which

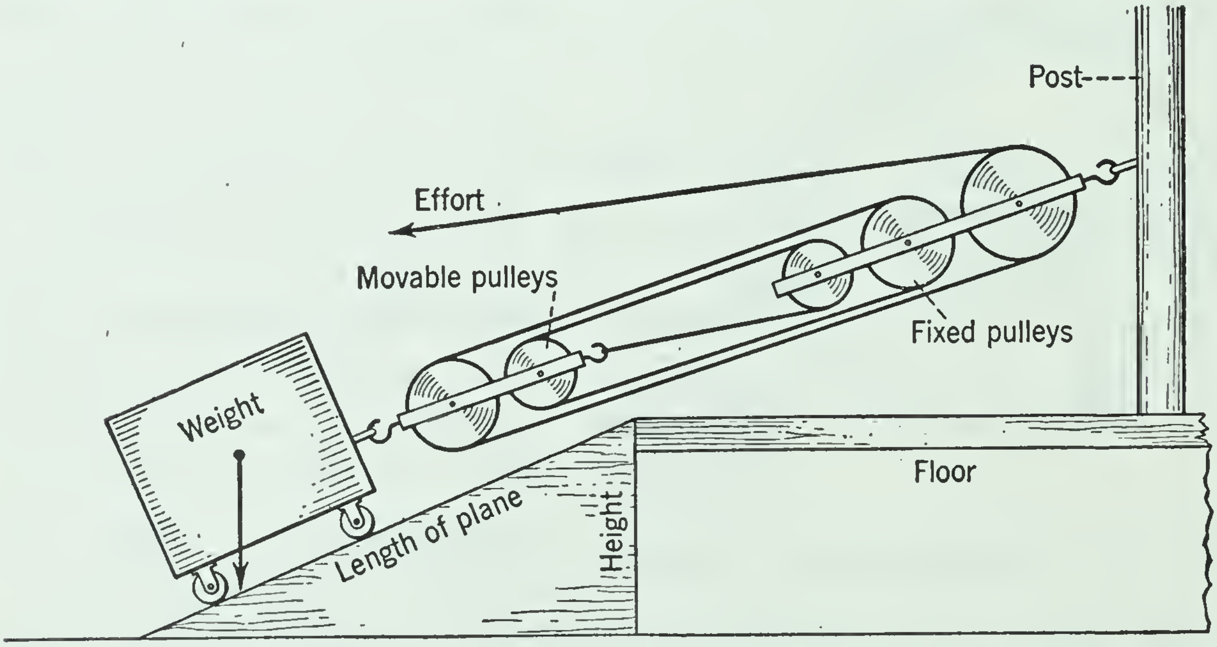


Fig. 4–46. The *MA* of a compound machine is usually the product of the *MA*'s of all the simple machines of which it is composed.

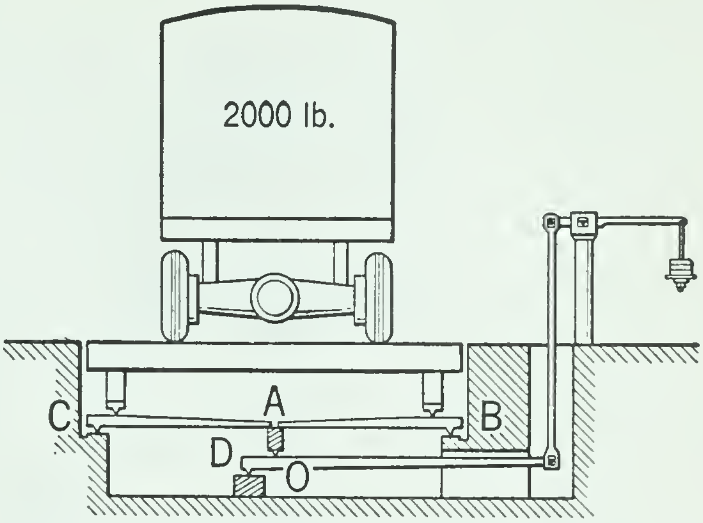


FIG. 4–47. The platform scales have several compound levers.

weighs 4000 lb. to be lifted to the floor. A gangplank 20 ft. long leads to the floor, which is 4 ft. high. The *MA* of the plane is 5, but an effort of 800 lb. is still required to pull the safe up the plank. If we attach a movable pulley to the safe and a fixed pulley to the post, we have a pulley system which has a mechanical advantage of 5. Hence it will take 160 lb. of effort applied to the rope to pull the safe up the incline. The total *MA* of the two machines is 5 × 5, or 25.

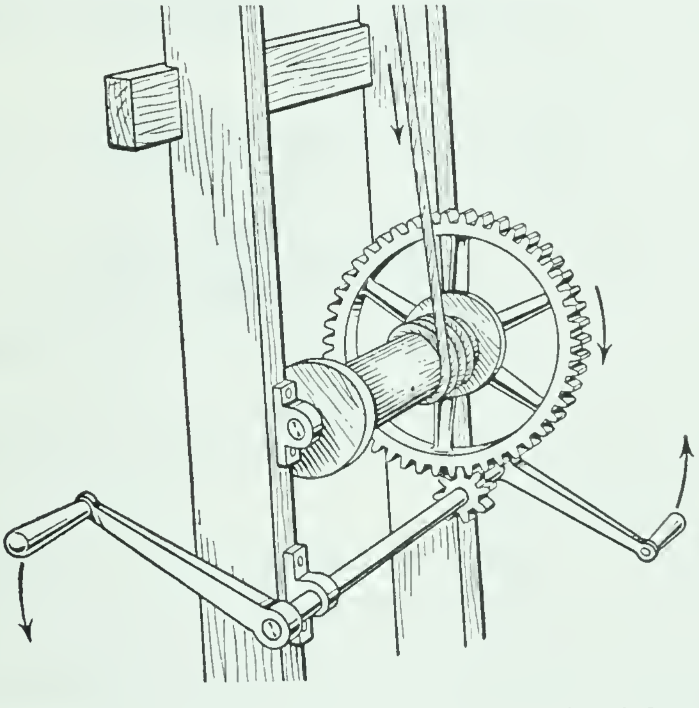


FIG. 4–48. A winch used with a derrick.

Formula for *MA*. In nearly all cases of compound machines, the *total mechanical advantage is the product of the separate mechanical advantages.* If one machine multiplies the effort by 5 and a second machine multiplies the effort by 5, then both acting together will multiply it by 25. (See Figs. 4–47, 4–48, and 4–49 for other examples of compound machines.)

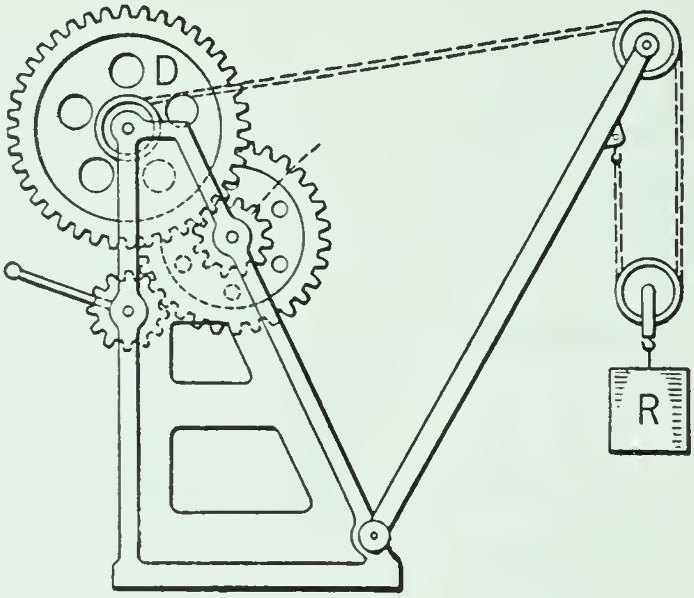


FIG. 4–49. The builder's crane.

SUMMARY

1. The lever is a rigid bar free to turn about a fixed point called the fulcrum. In all classes of levers:

$$\frac{\text{effort}}{\text{resistance}} = \frac{\text{resistance arm}}{\text{effort arm}}$$

$$MA = \frac{\text{length of effort arm}}{\text{length of resistance arm}}$$

2. The center of gravity of a body is that point at which all its weight appears to be concentrated.

3. Moment of force is equal to the force times the length of the arm upon which it acts.

4. Equilibrium of a lever is reached when the moments clockwise equal moments counterclockwise.

5. The stability of an object is increased by broadening its base and lowering its center of gravity.

6. The mechanical advantage of a block and tackle equals the number of strands supporting the movable block.

7. In the wheel and axle:

$$MA = \frac{\text{circumference of wheel}}{\text{circumference of axle}}$$

The diameters or radii may be substituted for the circumferences.

8. When the force or effort is applied parallel to the incline of an inclined plane:

$$MA = \frac{\text{length of plane}}{\text{height of plane}}$$

9. Mechanical advantage of the screw:

$$\frac{\text{circumference described by the effort}}{\text{pitch}}$$

10. The spur, pinion, bevel, helical, and worm gears are used as a means of transmitting power.

11. The total mechanical advantage of a compound machine is nearly always the product of the separate mechanical advantages of the simple machine of which it is made up.

12. The efficiency of any simple machine equals:

$$\frac{\text{useful work accomplished}}{\text{total work expended}}$$

13. Because we cannot eliminate either friction or the weight of the parts of machines, no machine is 100% efficient. Some levers, indeed, are nearly 100% efficient. The efficiency of a block and tackle is usually not more than 60%. Because of high friction, the jackscrew has an efficiency of only 25% or less.

How many of the following terms can you define or explain?

Center of gravity
Moment of force
Fulcrum
Equilibrium
Stable equilibrium
Unstable equilibrium
Neutral equilibrium
Equilibrant
Grade
Gear
Gear train
Compound machine

SELF-TESTING EXERCISES

ANSWER THESE QUESTIONS

On a separate sheet of paper numbered from 1 to 5 write the letters for the phrases that answer the following questions correctly.

1. Which of the following statements is true about the center of gravity of the body? (*a*) It is always in the center of the body; (*b*) it is the point at which all weight appears to be concentrated; (*c*) it has nothing to do with stability.

2. Which of the following statements is true about a moment of force? (*a*) It equals the product of force times the time in which it acts; (*b*) it is the same as force of gravity on a body; (*c*) it equals the product of force times the length of the arm upon which it acts; (*d*) it is measured in foot-pounds.

3. In which of the following ways may stability be increased? (*a*) By elevating the center of gravity; (*b*) by lowering the center of gravity; (*c*) by reducing the volume of the object.

4. Which of the following statements is correct? The efficiency of any machine equals the ratio of (*a*) Effort distance to weight distance; (*b*) total work expended to useful work accomplished; (*c*) work output to work input; (*d*) work input to work output.

5. Which of the following statements is true about a micrometer caliper? (*a*) It is a screw; (*b*) it is a wheel and axle; (*c*) it is a train of gears.

Complete These Statements

On a separate sheet of paper numbered from 1 to 9 write the words needed to fill correctly the blank spaces in the following sentences.

The ..(1).. is the point of pivot or rotation of a lever. An object is in ..(2).. when no unbalanced force acts upon it. Lowering the center of gravity of an object increases its ..(3)... The equilibrant of two forces is equal in magnitude but opposite in direction to the ..(4)... A pair of scissors is an example of a ..(5).. -class lever. From the standpoint of either pier, a simple bridge is a ..(6).. -class lever. The height which a road rises for each 100 feet of its length is called its ..(7)... Any combination of two or more cogwheels is known as a ..(8)... The total mechanical advantage of a compound machine is the ..(9)..of the separate mechanical advantages.

Are These True or False?

On a separate sheet of paper numbered from 1 to 6 write a T *or an* F *to show whether each statement is true or false.*

1. The law of machines cannot be applied to levers.

2. A rolling ball is an example of neutral equilibrium.

3. The mechanical advantage of a block and tackle is always equal to the number of strands.

4. The mechanical advantage of a screw is always high.

5. The transmission of a car is an example of a gear train.

6. The ratio of total work expended to total work accomplished is the mechanical advantage of any machine.

QUESTIONS

1. Determine the position of the effort, fulcrum, and resistance in each of the following: a claw hammer used for pulling nails (Figure 4–50); a pair of sugar tongs; a nutcracker; the oar of a rowboat; the lower jaw.

2. Where should the resistance be placed to get a high mechanical advantage with a second-class lever?

3. Where must the effort be placed with a third-class lever to get a high mechanical advantage of speed?

4. Draw diagrams to show how you would arrange at least two levers so that the weight of the lever really helps the effort counterbalance the resistance.

5. Draw a diagram to show a case where the weight of the lever is really a hindrance to the effort.

6. Why is it impossible to have a machine with an efficiency of more than 100%?

7. In a lever where the weight of the lever serves to aid the effort it may seem as if the efficiency is more than 100%. Where does the discrepancy occur?

8. Which of the two methods of finding the mechanical advantage of a machine is the more convenient? Explain why.

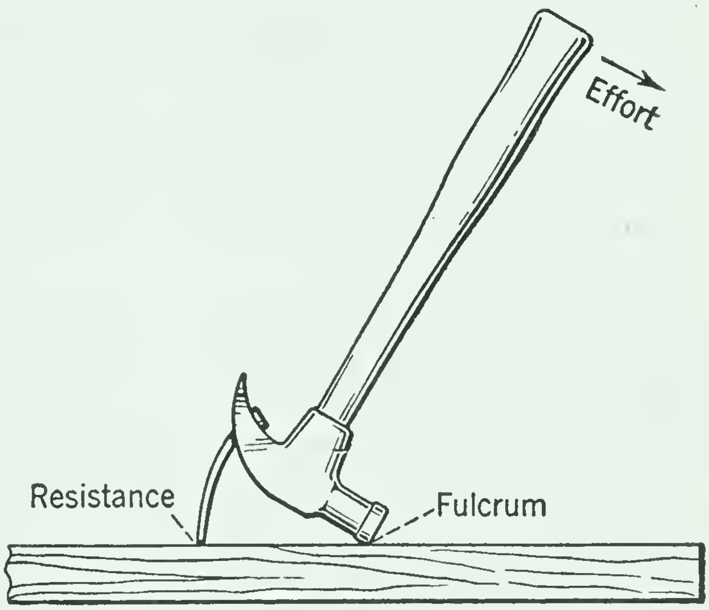


FIG. 4–50. The hammer in this figure is a bent lever of the first class.

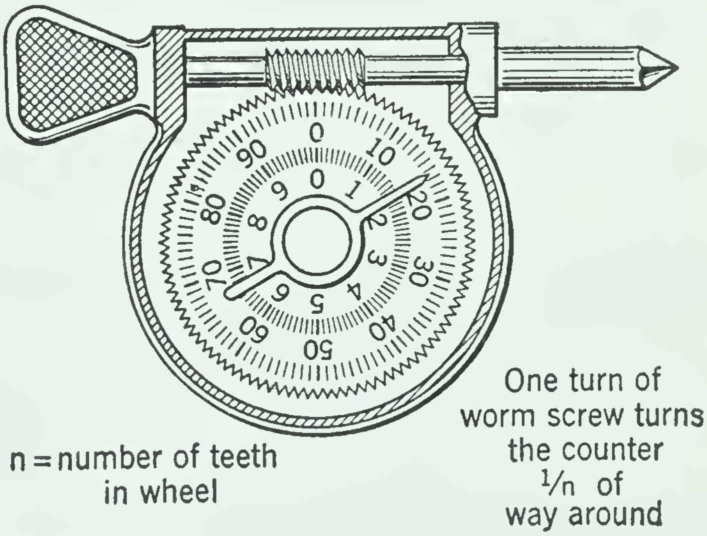

0
10
20
30
40
50
60
70
80
90
0
1
2
3
4
5
6
7
8
9
One turn of worm screw turns the counter 1/n of way around
n = number of teeth in wheel

FIG. 4–51. The worm gear can be used as a speed counter.

9. Make a list of ten simple machines used about the household and classify them.

10. Explain how the speed counter shown in Figure 4–51 can be used to determine the number of revolutions per minute.

11. What type of machine is a brace and bit, used for boring a hole in a plank?

12. Is it easier to bore a hole with a 1-in. bit, or with one that is $1\frac{1}{2}$ in. in diameter?

13. How heavy a load can a man lift with a single fixed pulley?

14. Study Figure 4–33. Show that a wheel and axle is a lever.

15. Make a list of at least six applications of the wheel and axle as used around the house.

16. What type of machine is a screw driver?

17. What type of machine is a jackknife? A cold chisel?

18. Why does a large grindstone with a short crank turn hard? What type of machine is it?

19. The turnbuckle of Fig. 4–52 acts upon one rod which has a right-handed screw; it also acts upon another rod which has a left-handed screw. If each rod has 12 threads to the inch, how much is the space between the ends increased or decreased by one complete turn of the turnbuckle?

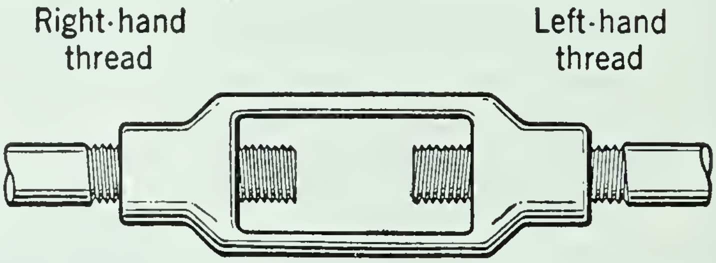


Fig. 4–52. The turnbuckle.

20. What is the meaning of the expression, "The gear ratio in the differential of an automobile is 4.5"?

PROBLEMS

1. A man uses a plank 15 ft. long as a lever of the second class. Neglecting the weight of the plank, what effort is needed to lift a resistance of 500 lb. placed 3 ft. from the fulcrum?

2. What effort will be needed to lift the load of problem 1 if the plank is used as a first-class lever? (Load 3 ft. from fulcrum.)

3. A boy weighing 90 lb. sits on one end of a seesaw, 6 ft. from the fulcrum. A second boy is 9 ft. from the fulcrum. What is his weight, if the seesaw is counterbalanced?

4. A bar 8 ft. long is to be used as a lever of the second class. How far from the fulcrum must the resistance be placed if a force of 80 lb. is to balance 600 lb.?

5. What mechanical advantage is needed for 60 lb. to counterbalance

240 lb.? Make a diagram of a first-class lever 10 ft. long with the effort, fulcrum, and resistance properly arranged to give such an advantage.

6. A man has a fishing pole 15 ft. long. One hand at the end of the pole acts as the fulcrum, and the other hand, 1 ft. from the end, as the effort. What effort is needed to pull from the water a 5-lb. fish?

7. A uniform bar 8 ft. long weighs 24 lb. What weight must be applied to one end of the bar to make it balance on a fulcrum placed just 1 ft. from that end?

8. A meter stick loaded at one end balances on a fulcrum placed 20 cm. from the loaded end. When a weight of 500 gm. is attached to the unloaded end, the combination balances on a fulcrum placed 35 cm. from the 500-gm. weight. Find the weight of the loaded meter stick.

9. Draw a system of fixed and movable pulleys so arranged that 1 lb. will counterbalance 3 lb.

10. Make a diagram of a system of fixed and movable pulleys having a mechanical advantage of 6.

11. Two men operate a windlass. If the wheel has a diameter of 3 ft. and the axle a diameter of 6 in., what effort must each one use to overcome a resistance of 1800 lb.? How many complete turns of the wheel will be needed to lift the load 12 ft.?

12. The steering wheel of an automobile is 16 in. in diameter and the shaft to which it is attached is 1.25 in. in diameter. What resistance applied to the shaft can be overcome by a tug of 20 lb. on the wheel?

13. The handle of a screw driver is 1.5 in. in diameter and the blade is 0.375 in. wide. What is the mechanical advantage gained by the use of the screw driver? Is the screw driver a lever?

14. In a system of pulleys the effort moves 8 ft. in order to lift the resistance 1 ft. If the effort is 60 lb. and the useful load is 360 lb., what is the efficiency of the pulley system?

15. A boy can exert a force of 60 lb. How long a plank must he get if he is to roll a barrel weighing 240 lb. up into a wagon 3 ft. high? (Neglect friction.)

16. One end of a gangway 20 ft. long is 4 ft. higher than the other. It takes 75 lb. of effort to roll a 300-lb. barrel up the plank. What is the efficiency?

17. A 50-horsepower engine hoists 100 tons of coal per hour from a mine 440 ft. deep. What is its efficiency?

18. A man uses a plank 15 ft. long to roll a barrel weighing 360 lb. to a floor 3 ft. high. If the plank weighs 100 lb., how many ft.-lb. of work did the man do in putting the plank into position? If one neglects friction, what force must the man use to roll the barrel up the plane?

19. If it is found that the man does 1200 ft.-lb. of work in rolling the barrel up the plane in problem 18, what is the efficiency of the plane?

20. How much force must a horse exert to pull a wagon weighing 800 lb. up a 3% grade? (Note that the road rises 3 ft. for 100 ft. of length, which in this case is the base of the triangle.)

21. If an engine works at an efficiency of 100%, what H.P. engine will be required to lift 10,000 lb. to a height of 220 ft. in 5 minutes?

V

Machines Utilize the Hydraulic Principle

In our work with machines, we have to pay frequent attention to liquids in motion, to the pressure exerted by a liquid on the bottom of its container, and to pressures which are applied to a liquid in a closed container. Here we are dealing with the subject of *hydraulics*. "The hydraulic principle," as we shall use it in this book, refers to these various pressures of liquids.

A. LIQUIDS EXERT AND TRANSMIT PRESSURE

1. BY GRAVITY (FUEL-FEED SYSTEMS)

What is pressure? We have already defined *force* as a push or a pull generally measured in grams or in pounds. We use the term *pressure* to indicate the force which is applied to a unit area. For that reason, we measure pressure in *lb. per sq. in.*, or in *gm. per sq. cm.* Total force is measured in pounds or grams, since it applies to the force acting against the total area of some particular surface.

How do liquids exert pressure? Suppose we have a large wooden tank filled with water or some other liquid. If we bore a hole in the bottom of the tank, the liquid will flow out, thus proving that liquids push *downward* upon the bottoms of their containers. This is what one might expect, since liquids have weight. If we bore a hole in one side of the tank, the liquid will flow out through this opening, proving that liquids exert pressure in a *sidewise* direction, too. If we push a piece of wood down into a vessel of water, it will rise to the surface of the water again as soon as it is released. One must use force to *hold* a block of wood beneath the surface of the water. Evidently the water must exert an *upward* push upon the block of wood. The upward push which liquids exert upon objects submerged in them causes some objects to lose all their apparent weight and to float, and it causes dense objects to lose part of their weight. Therefore, we conclude that liquids exert pressure in all directions, *downward, sidewise,* and *upward.*

Liquid pressure is proportional to the depth. Just as a brick lying on a table presses upon the table, so water or any other liquid poured into a vessel exerts force or pressure upon the bottom of the vessel. Such force is due to the weight of the liquid. When several bricks are piled upon one another, the downward pressure is increased. Likewise, every layer of liquid bears the weight of the layer directly above it; hence the *pressure of a liquid increases in direct proportion to the depth.* If the unit area pressed upon is 1 sq. cm., as in Figure 5–1, then water 1 cm. deep exerts a pressure of 1 gm., which is the weight of 1 cc. of water; the pressure at a depth of 2 cm. equals 2 gm.; for each cm. increase in depth the increase in pressure is 1 gm. If the unit area pressed upon is 1 sq. ft., water 1 ft. deep exerts a pressure of 62.4 lb. This is also the weight of 1 cu. ft. of water. You must picture in your imagination that 1 cu. ft. of water rests upon a base having an area of 1 sq. ft. On each sq. in., the pressure of water is $\frac{1}{144}$ of 62.4 lb., or *0.433 lb. for each ft. in depth.*

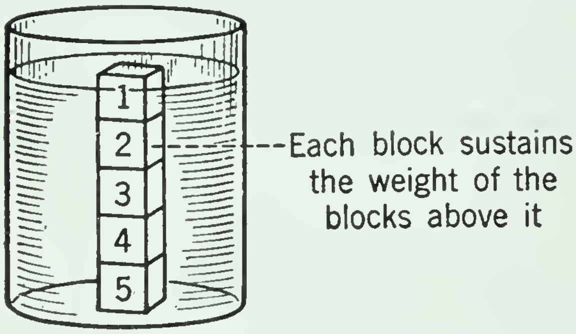


Fig. 5–1. Liquid pressure increases with the depth of the liquid.

Demonstration. Drill three or four holes at different heights in the side of a tall tin can (or milk container) and fill it with water. Does the water squirt equal distances from all the holes? Explain.

Liquid pressure is proportional to density. Liquids vary in density. Mercury is a dense liquid, weighing 13.6 times as much as an equal volume of water. Since the pressure caused by liquids is due to the weight of the liquid, we should expect mercury to exert much greater pressure than water of the same depth. Experiment shows that it does. *The pressure exerted by a liquid is directly proportional to its density.* We have learned that water 10 cm. deep exerts a pressure of 10 gm. Mercury 10 cm. deep exerts a pressure of 136 gm. (10 × 13.6 gm.). Since gasoline is only about 0.7 as dense as water, the pressure exerted at a depth of 10 cm. in gasoline is only 7 gm. (10 × 0.7 gm.). Put in the form of an equation:

$$\textbf{pressure} = \textbf{depth} \times \textbf{density}$$

Using the letter p to represent pressure, h for depth, and d for density, the equation becomes:

$$p = hd$$

PROBLEM. A diver goes down to a depth of 150 ft. in sea water; density equals 64 lb./cu. ft. Calculate the pressure on each sq. ft. of his body. Calculate the pressure on each sq. in. of his body.

Solution. The depth h is given as 150 ft.; and the density d is 64 lb./cu. ft. The pressure p is required. Substituting these values in the formula, $p = hd$, then $p = 150 \times 64$, or 9600 lb. on each sq. ft. To find the pressure in pounds per sq. in., we divide 9600 lb. by 144, the number of sq. in. in 1 sq. ft. The quotient is 66.7 lb.

PROBLEM. For fighting fire in a certain city, water must be supplied at a pressure of 150 lb. per sq. in. How high must a reservoir be above the city to supply such pressure?

Solution. p = 150 lb. per sq. in.; d = 62.4 lb./cu. ft.; h is unknown. From the equation:

$$p \text{ (in lb. per sq. in.)} = \frac{h \text{ (in ft.)} \times d \text{ (in lb. per cu. ft.)}}{144}$$

Substituting,
$$150 = \frac{h \times 62.4}{144}.$$

Then, $150 \times 144 = h \times 62.4$. Therefore, $h = 346.1$ ft.

How is liquid pressure affected by direction? A pile of bricks resting on a table exerts pressure in a *downward* direction only, because the bricks are solid and their molecules do not move over one another freely. The molecules of a liquid, however, move over one another so freely that a liquid takes the shape of its container; therefore we may expect liquids to press outward in a *sidewise* direction. Our study of floating objects convinces us that liquids push *upward* toward the surface as well as *downward* and *sidewise.*

To illustrate, we may pour mercury into the three tubes shown in Figure 5–2 until it stands at the same height in each, and then lower them all into water so that the open ends are at the same depth. The pressure of the water will cause the mercury to rise in the long arm of each tube. At *A* the water presses *downward;* at *B* the pressure is *upward;* while at *C* a *sidewise* pressure is exerted. The mercury stands at the same level in the long arm of each tube. As measured by the mercury columns the pressures are all equal. This is one way of showing that *liquid pressure is independent of direction.*

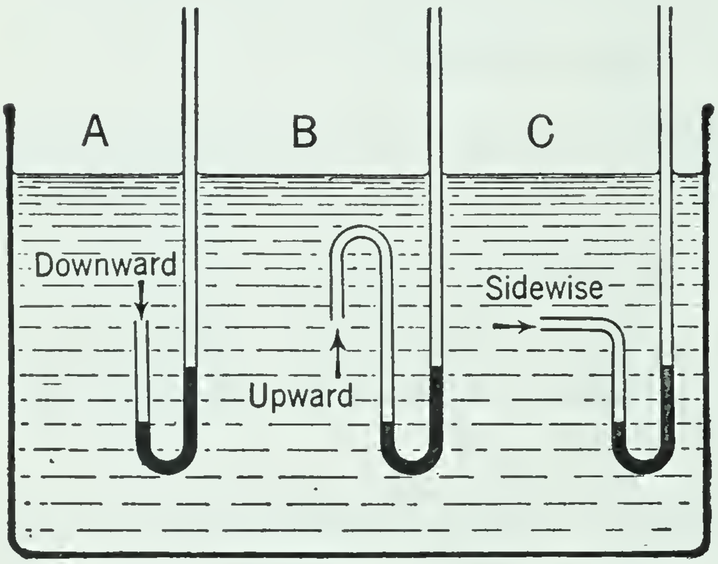


FIG. 5–2. Liquid pressure does not depend upon the direction.

Let us try to picture a drop of water in the center of a glass of water. The pressure upon this drop of water must be *equal in all directions,* or currents would be produced in the water.

How does the shape or area of the container affect liquid pressure? Since pressure is measured in terms of unit area, such as lb. per sq. in., or gm. per sq. cm., we need not consider the *total* area in solving problems dealing with liquid pressure. The area of the liquid surface inside a teakettle is much greater than that of the liquid in the spout, but the pressure is the same in both cases. If the pressure increased with the area, water would always flow out of the spout of the teakettle.

From these facts we should expect liquid pressure to be independent of the *shape* of the container and so it is. Pascal's vases may be used to demonstrate this fact. (See Fig. 5–3.) The area of the diaphragm at the bottom of these vases is the same, and it may be considered as unity. A pointer used to show the increase in pressure as water is poured into these vases indicates the same pressure for all three vases, although their shapes are different and the total amount of water is also different. Liquids stand at the same height in communicating vessels, no matter what their shape. (See Fig. 5–4.) We conclude that *liquid pressure is independent of the shape and area of the container.*

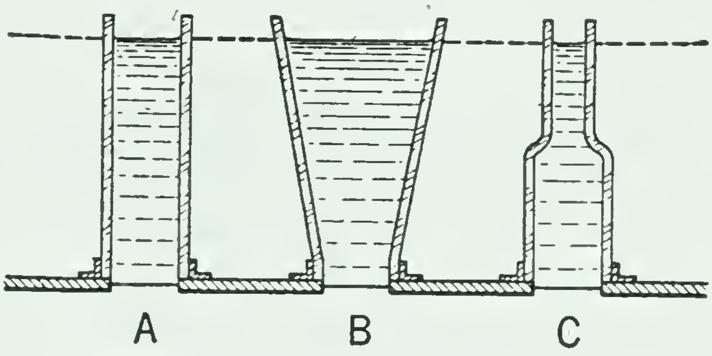


Fig. 5–3. Liquid pressure is independent of the shape or the area of the container.

In conclusion, we may summarize the following LAWS OF LIQUID PRESSURE:

(1) *Liquid pressure is directly proportional to the depth of the liquid.*

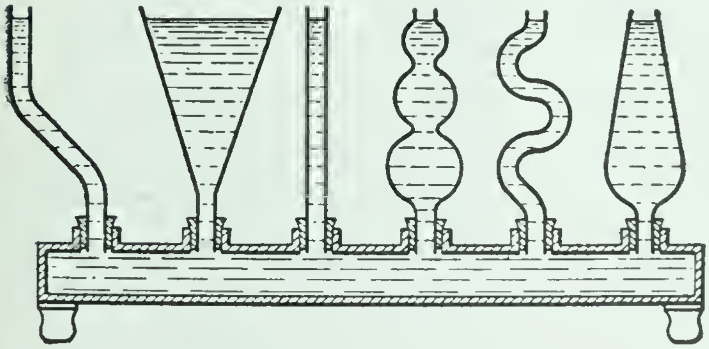


Fig. 5–4. Liquids in connecting vessels stand at the same height.

(2) *Liquid pressure is directly proportional to the density of the liquid.*

(3) *Liquid pressure is independent of the area or shape of the container; it is also independent of direction.*

Explain direct and inverse proportion. The terms *direct proportion* and *inverse proportion* are used frequently in stating facts and laws in physics. *Two quantities are directly proportional to each other when an increase or decrease in one of them produces a corresponding increase or decrease in the other.* In the formula $p = hd$ (page 117) we observe that an *increase* in the depth of a liquid *increases* the pressure, and that an *increase* in the density of the liquid *increases* the pressure.

Two quantities are inversely proportional to each other when an *increase in one of them produces a corresponding decrease in the other.* If we squeeze a tennis ball, its volume becomes smaller. Suppose we refer to the formula for density:

$$D = \frac{W}{V}$$

We see that an *increase* in W without any change in V causes an *increase* in D; an *increase* in V without any change in W causes a *decrease* in D. Hence, the density of an object is *directly* proportional to its weight and *inversely* proportional to its volume.

Let us plot a graph or curve to show direct proportion, using data obtained by experiment.

Depth of 1 cm., pressure equals 1 gm.
Depth of 3 cm., pressure equals 3 gm.
Depth of 5 cm., pressure equals 5 gm.
Depth of 9 cm., pressure equals 9 gm.
Depth of 12 cm., pressure equals 12 gm.

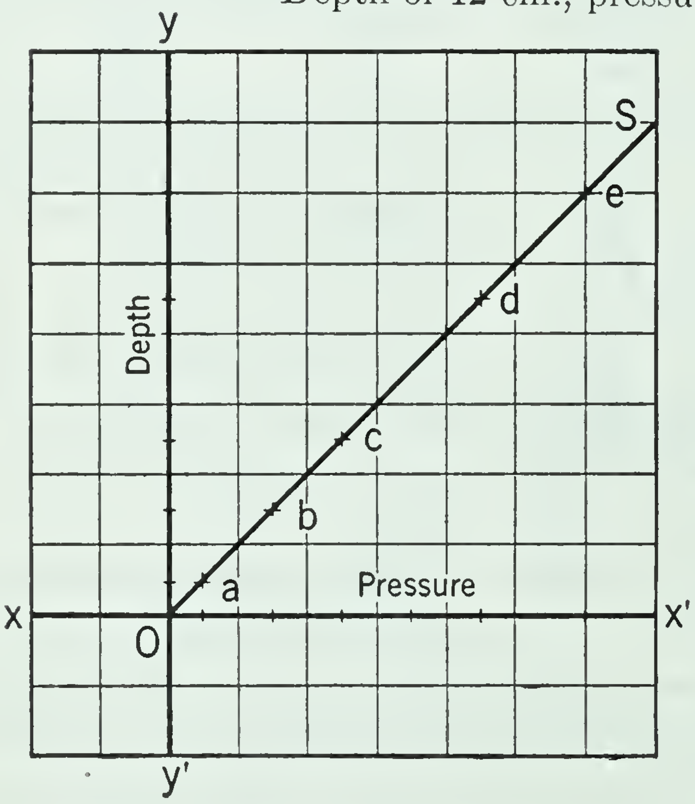


Fig. 5–5. The direct proportion curve shows that the pressure increases as the depth increases.

Suppose that we let O represent the origin of the graph, Figure 5–5, and measure off on the line xx' distances equivalent to the various pressures. For convenience let us use one small space to represent one gram. Next let us measure off on the line yy' distances *equivalent* to the depth in cm., using one small space to represent 1 cm. Point a represents a pressure of 1 gm. at a depth of 1 cm.; point b represents a pressure of 3 gm. at a depth of 3 cm. In a similar manner we locate the points c, d, and e, and draw a line from the origin of the curve through all these points. This line, OS, is a curve of *direct proportion.*

How can we find the total force on the bottom of a container? We have learned that the *pressure* which a liquid exerts, on the bottom of a containing vessel, for example, equals the product of the depth and the density. While engineers refer to pressure in lb. per *sq. in.*, it will generally be more convenient for us to use the *sq. ft.* as the unit area. On the bottom of a tank containing water 10 ft. deep, the pressure on each *sq. ft.* equals depth (10 ft.) × density (62.4 lb. per cu. ft.) or 624 lb. per *sq. ft.* This is equal to 4.33 lb. per *sq. in.*

NOTE. While the following suggestion may not accord with *formal* mathematics, yet it does aid the beginner. Let us write, $d = 62.4\,\frac{\text{lb.}}{\text{cu. ft.}}$. As we multiply, $10\text{ ft.} \times 62.4\,\frac{\text{lb.}}{\text{cu. ft.}}$, suppose we assume that the denomination *ft.*, which in the numerator represents depth, will change the *cu. ft.* in the denominator to *sq. ft.* By cancellation:

$$10\,\cancel{\text{ft.}} \times 62.4\,\frac{\text{lb.}}{\cancel{\text{cu. ft.}}\ (\text{sq. ft.})}$$

Therefore, pressure $= 624\,\frac{\text{lb.}}{\text{sq. ft.}}$

Since pressure is the force acting on *unit area*, to find the *total force* acting on the bottom of a vessel we merely multiply the *area* by the *pressure*. Stated algebraically:

total force = *area* × *pressure*, or
total force = *area* × *depth* × *density*

By using F to represent total force, A for area, h for depth, and d for density, the formula becomes:

$$F = Ahd$$

PROBLEM. A box 10 ft. long, 8 ft. wide, and 6 ft. deep is full of water. Find the total force on the bottom of the box.

Solution. The area pressed upon is 10 ft. × 8 ft., or 80 sq. ft.; the depth of the water is 6 ft., and its density $62.4\,\frac{\text{lb.}}{\text{cu. ft.}}$.

total force = area × depth density

total force $= 80 \times 6 \times 62.4\,\frac{\text{lb.}}{\text{cu. ft.}}$. The answer is 29,952 lb.

NOTE. In the foregoing problem, suppose we assume that the *sq. ft.* of the area times *ft.* in depth completely *cancel* the *cu. ft.* in the denominator as follows:

$80\ \cancel{\text{sq. ft.}} \times 6\ \cancel{\text{ft.}} \times 62.4\ \frac{\text{lb.}}{\cancel{\text{cu. ft.}}}$. Therefore, the answer is 29,952 *pounds.*

PROBLEM. Find the total force on the bottom of a box 3 m. long, 2 m. wide, and 1 m. deep, if the box is full of water.

Solution. Changing m. to cm., we have 300 cm. × 200 cm. × 100 cm. The area pressed upon is 300 cm. × 200 cm., or 60,000 sq. cm.; the depth is 100 cm.; and the density is $1\ \frac{\text{gm.}}{\text{cc.}}$.

By substituting in the formula, total force will equal $60{,}000 \times 100 \times 1\ \frac{\text{gm.}}{\text{cc.}}$. The answer is 6,000,000 gm. If we solve the problem by using meters, then we get 6 metric tons as our answer.

How can you find the total force on the side of a containing vessel, or against a dam? Everybody knows the story of the Dutch boy at the dike. As he stopped the small hole in the dike, he was resisting the sidewise pressure of the sea. As the soil around our houses fills with water, the sidewise pressure may become great enough to push the water through our cellar walls. In building a dam, engineers must calculate the total force which the water will exert against the side of the dam. We know that in our calculations we must always use for the area the *area of the surface pressed upon.* We know, too, that pressure is independent of direction, but we must consider what depth to use.

Imagine that the room in which you are sitting is full of water. Its length is 15 ft.; its width is 12 ft.; and its ceiling is 8 ft. high. The area of the longer side of the room is equal to the length, 15 ft., multiplied by the height of the wall, 8 ft. The *area pressed upon* is 120 sq. ft. The water is 8 ft. deep at the floor; at the ceiling the water is 0 ft. deep. From Figure 5–6 we see that the depth varies. Halfway up the wall, the water is 4 ft. deep; 3 ft. from the floor, the water is 5 ft. deep; and 3 ft. from the ceiling the water is 3 ft. deep. The *average depth* is 4 ft.

$$\frac{0+3+4+5+8}{5} = 4$$

Since the depth of a vertical surface varies, we must use the *average depth.* Then the total force on the wall of the room = 120 sq. ft. (area) × 4 ft. (average depth) × 62.4 $\frac{\text{lb.}}{\text{cu. ft.}}$ · The force is equal to 29,952 lb.

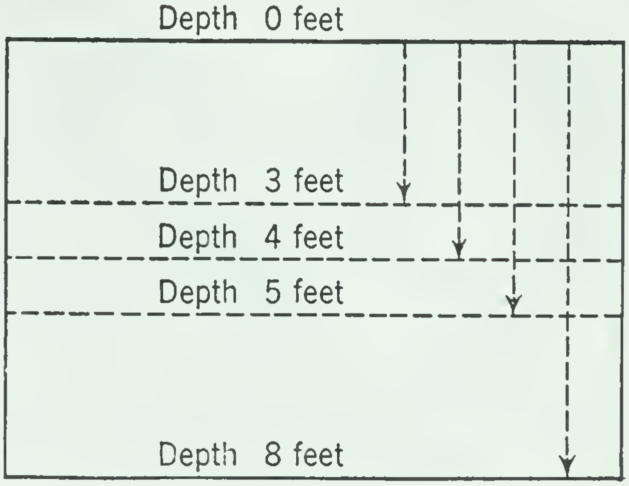


FIG. 5–6. The pressure against a vertical surface varies with the depth.

In any case, total force equals the area of the surface pressed upon times the average depth times the density. For *horizontal* surfaces the depth is uniform at all points. Hence, $F = Ahd$. For *vertical* surfaces, the average depth is usually equal to *half* the depth.

$$F = A\tfrac{h}{2}d$$

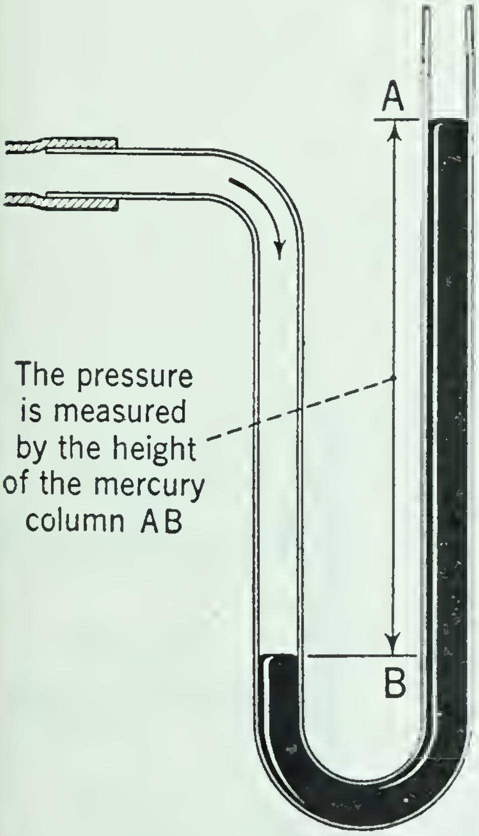

A
B
The pressure is measured by the height of the mercury column AB

FIG. 5–7. The open manometer may be used to measure pressure.

How is pressure measured? Occasionally the water pressure in some cities becomes low in dry weather. To be certain that the pressure is great enough to fight fires effectively, a pressure gauge of some kind is used. An *open manometer* is shown in Figure 5–7. Here the pressure of the water is balanced against a column of mercury. The manometer, which is partially filled with mercury, is attached to the faucet and the water is turned on. The pressure is measured by the height of the mercury column *AB*. If the tube has a cross-sectional area of 1 sq. in., the weight of the mercury column in pounds equals the pressure of the water in lb. per sq. in. Sometimes a *closed manometer* is used, but more often water pressure is measured by means of a spring gauge, which is calibrated to read

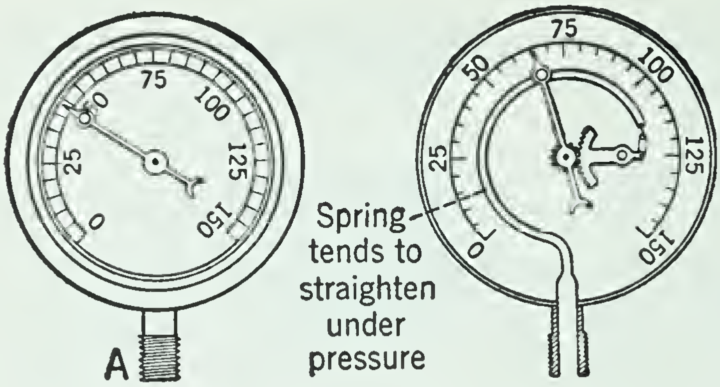


Fig. 5-8. The Bourdon pressure gauge. Sectional view at right.

directly in pounds per square inch. (See Fig. 5-8.) The pressure of the water tends to straighten out the flat, curved tube, which is attached at one end to a lever geared with the pointer.

The expression "head of water" or "water head" is commonly used by engineers. If the *difference* of levels in communicating pipes is 144 ft., the water head is said to be 144 ft. Such a water head produces a pressure of 62.4 lb. per sq. in., because a water column of one sq. in. cross-sectional area and 144 ft. high has a volume of just one cubic foot. If we refer to Figure 5-9, we can understand why the water head on the different floors of the same building is not the same.

What are some applications of water pressure? (1) *Water seeks its level.* Water stands at the same height in communicating vessels, whatever their shape or relative area. The water in the spout of a teakettle stands at the same level as the water in the kettle. If we picture the surface of the water in a tank as having momen-

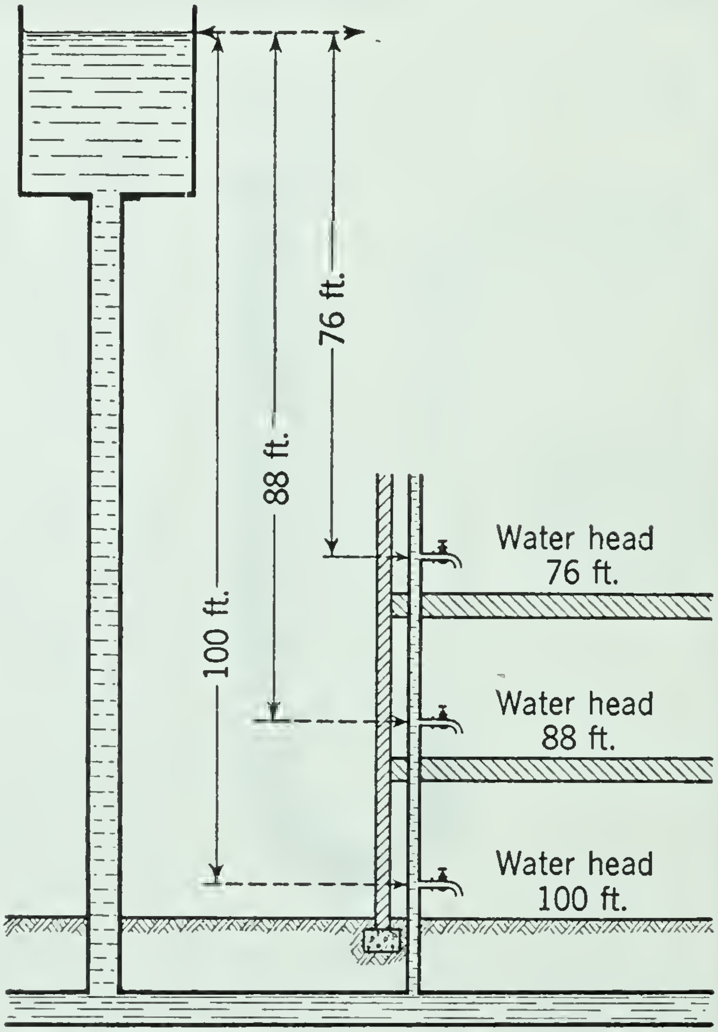


Fig. 5-9. The water head is greater at the lower floor. The effective pressure is least at the tap on the top floor.

tarily the form shown in Figure 5–10, we can understand why water seeks its level. The water heads at A and B are greater than at C. Hence the greater pressure at these points will cause the water to flow in the directions shown by the arrows until the surface is level. The water-gauge on a steam boiler is another application. (See Fig. 5–11.) If you have a steam boiler in your basement, the level of the water in the glass gauge shows the level of the water inside the boiler.

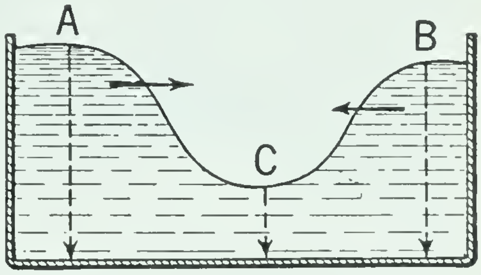


Fig. 5–10. Water flows until its surface becomes level.

The water supply for some cities is drawn from a reservoir higher than any part of the city itself. Since water seeks its level, it readily rises through the water pipes in the houses to the taps or faucets. If, however, part of a tall building happens to be higher than the level of the reservoir, then the upper floors of such a building will be without water and cannot have adequate fire protection. Such a building may be supplied from a tank on the roof or by means of a pump which forces the water to the highest parts of the building. Many cities are forced to install pumping stations. The pump forces water from the reservoir up into the standpipe, where it is stored. (See Fig. 5–12.) Sometimes a high-pressure pumping system is installed for fighting fires. (See. Fig. 5–13.)

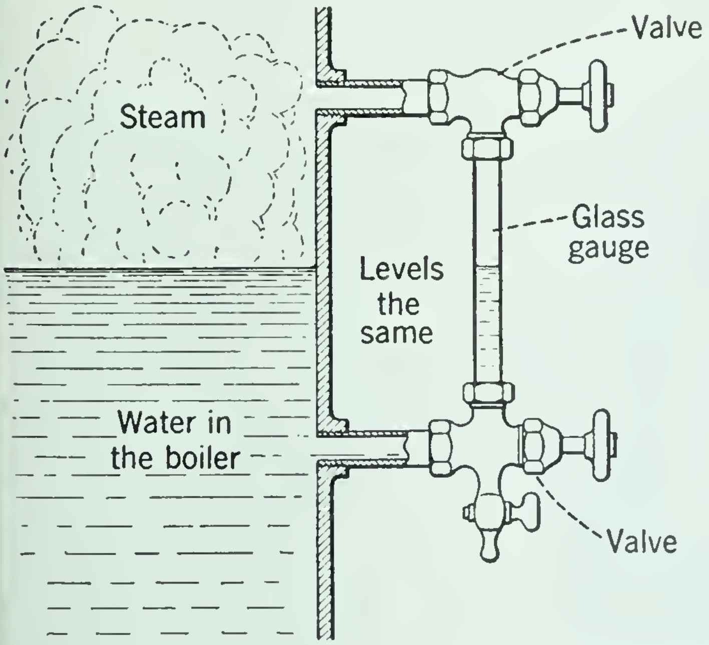


Fig. 5–11. Water in glass gauge stands at level of liquid in boiler.

The *artesian well* is another example of the fact that water seeks its level. (See Fig. 5–14.) We have a layer of water-saturated

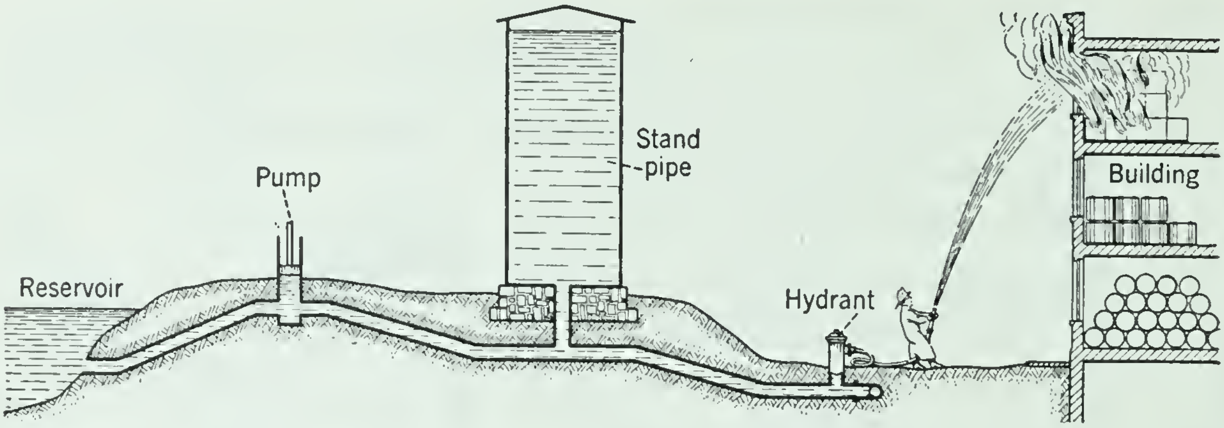


FIG. 5-12. Water from reservoir is pumped to standpipe. It flows to hydrant and exerts enough pressure to be effective in fighting fires.

gravel between two strata of impervious or nonporous rock. The water levels at A and B are higher than the level at W. Hence water gushes out to form a flowing well or fountain at W.

(2) *Submerged bodies must withstand pressure.* Probably the bottom of your cellar wall is at least 4 ft. below the water table when snow and ice are melting in the spring. That means that water is exerting a pressure of 4 × 0.433 lb. on every square inch of the bottom of our cellar walls. A pressure of 1.7 lb. per sq. in. may be sufficient to push the water through the pores of the concrete wall and cause water to enter our cellar.

Submarines must have very strong walls to resist the crushing force of the water, since the pressure increases as the submarine sinks deeper and deeper. The hull of a steamship must be very strong to resist pressure.

Courtesy of the Seagrave Corporation

FIG. 5-13. To fight city fires effectively, high water pressures must be used.

If you dive to a depth of 10 ft., the water pressure on every square inch of your body is more than 4 lb. At 100 ft. the pressure increases to more than 40 lb. per sq. in. Deep-sea divers have descended to a depth of more than 300 feet.

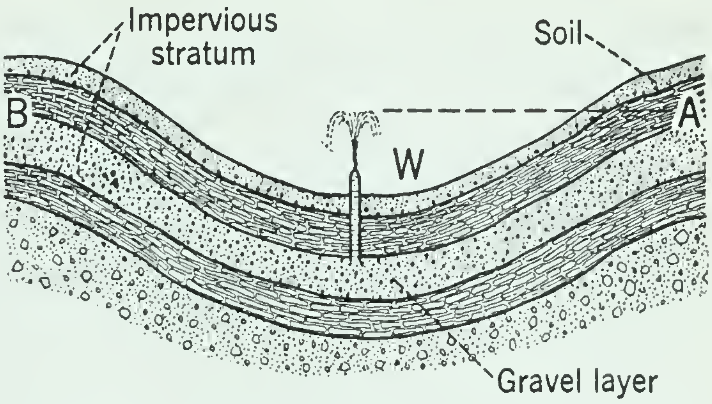
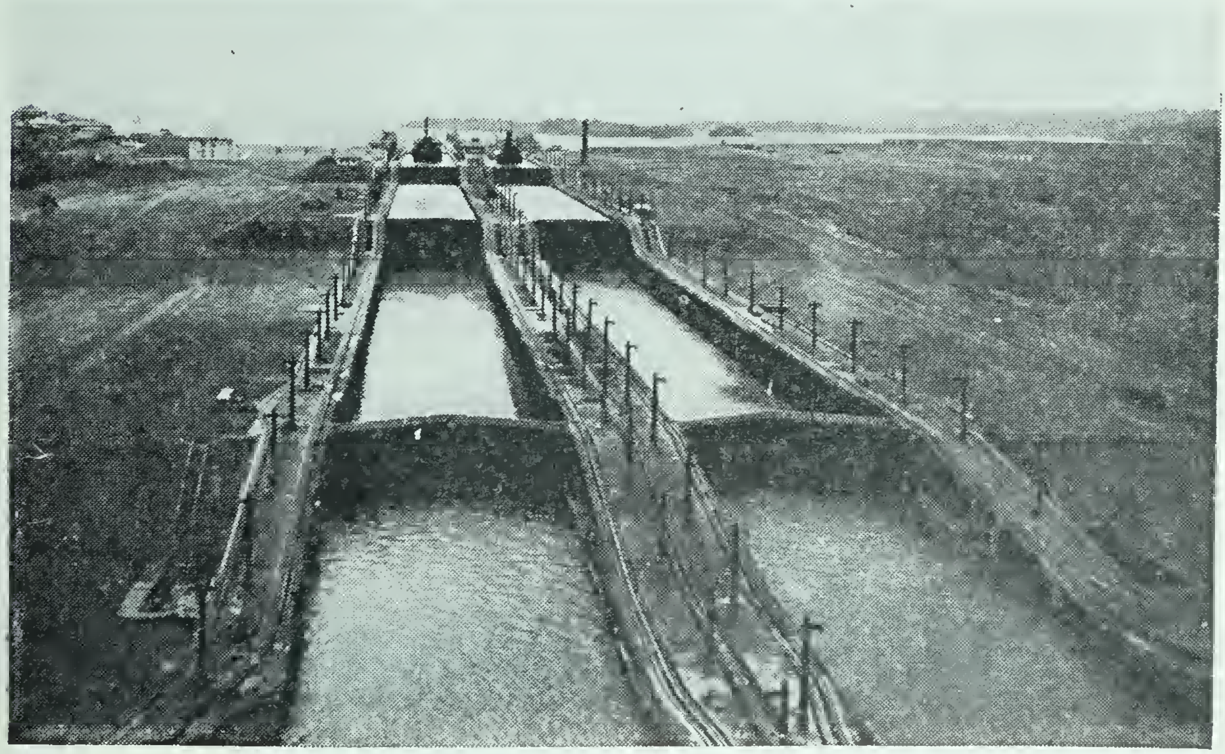


Fig. 5–14. Water from gravel layer forces water out through the opening at *W*.

(3) *Total force as related to construction work.* Before building cisterns, tanks, standpipes, dams, and canal locks, the engineer must compute the pressure or the total force to which these structures will be subjected. The amount of material used in constructing dams for storage reservoirs is enormous. Figure 5–15



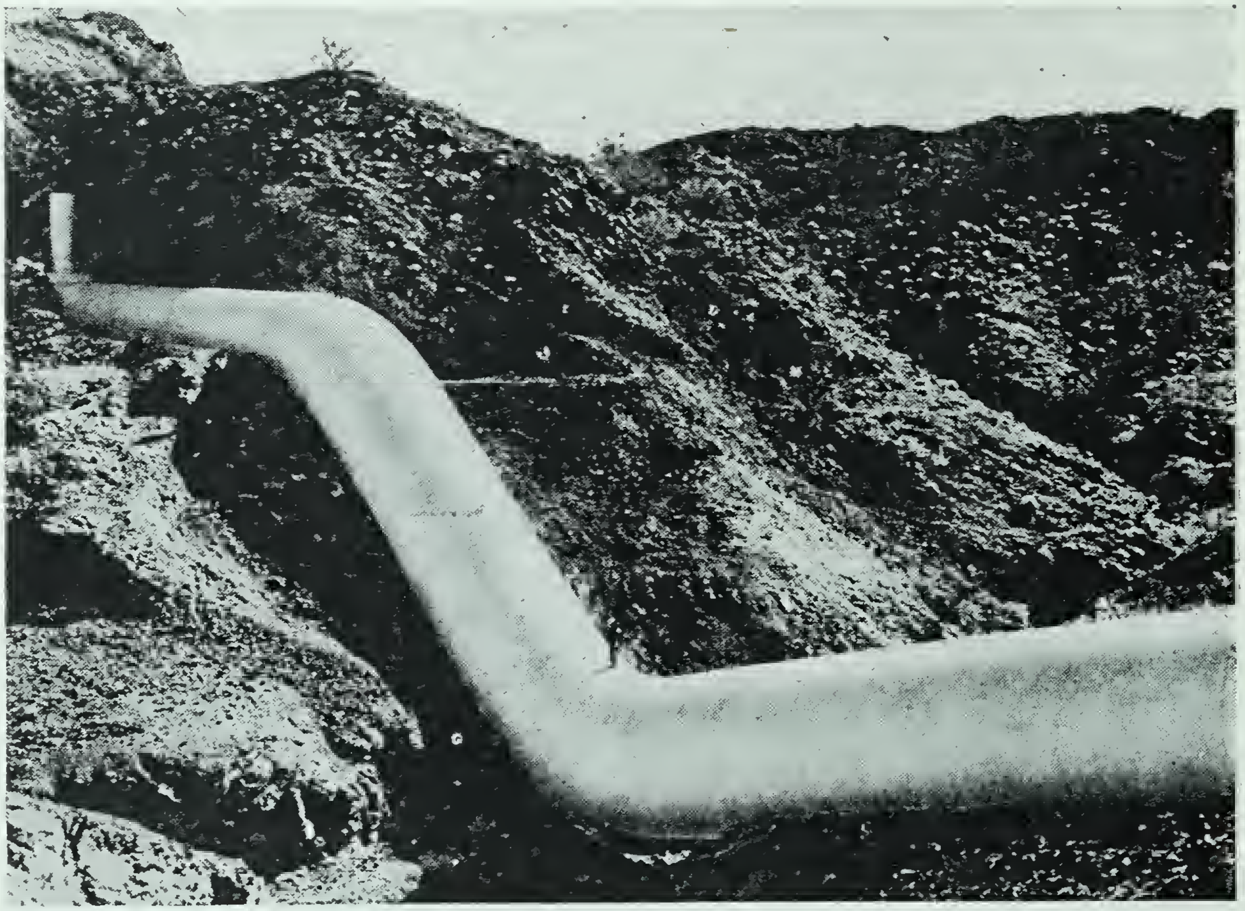
Courtesy of the War Department

Fig. 5–15. The Panama Canal locks are 1000 ft. long, 110 ft. wide, and the minimum depth of the water is 41 ft. The steel gates are 7 ft. thick and 65 ft. long. They are from 47 to 82 ft. in height. They weigh from 300 to 600 tons each. The building of the Panama Canal is one of the triumphs of engineering. The manufacturers of the steam shovel boast that their machines made the digging of the canal possible.

gives an idea of the enormous strength that canal locks must have, to withstand the total force of the water when the gates are closed.

(4) *Fuel-feed systems.* Pressure caused by the weight of liquids is called *gravity pressure.* Gravity pressure is useful in transmitting liquids from a higher to a lower level. Early models of automobiles (Ford's Model T, for example) used the gravity fuel-feed system. The fuel tank had to be higher than the carburetor. This system is still in use in trucks and tractors the design and construction of which permit the necessary elevation of the gasoline tank.

Aqueducts, such as the one shown in Figure 5–16, have to withstand pressures equivalent to a depth of more than 1600 ft. of water or about 700 lb. per sq. in.



Courtesy of the Metropolitan Water District

FIG. 5–16. This 16-foot aqueduct carries water from the Colorado River 392 miles to Los Angeles and other cities in Southern California. It carries about a billion gallons of water daily. Having a capacity of about 400 barrels per second, it dwarfs other famous aqueducts, ancient and modern. It consists of tunnels, conduits built of concrete, steel pipe, and canals lined with concrete. At some places it crosses elevations more than 1600 feet in height. Notice the appearance of the men standing on the aqueduct.

2. PASCAL'S LAW

How do liquids transmit the pressure applied to them? The liquid pressure which we have been studying may be called *weight pressure* since it is due to the weight of the liquid itself. Solids also exert pressure on account of their weight, but not in a sidewise direction. If we put one end of a meter stick against the floor and push on the other end, it *transmits the pressure* to the floor in the direction in which the force acts. Since the stick is rigid, it transmits the pressure in *only one* direction. Suppose that we put a stopper in one end of an iron pipe and completely fill the pipe with water. As a second stopper is pushed into the open end of the pipe, the first stopper is pushed out because the pressure is transmitted to it by the liquid in the pipe. Liquids are not easily compressed and readily transmit pressure. Now suppose that we drill several small holes in the pipe and repeat the experiment. As the second stopper is pushed into the pipe, the liquid squirts out through the holes, proving that pressure applied to a confined liquid is *transmitted in all directions.* This is what we might expect since we know that the molecules of liquids move freely and slide over one another readily.

For the same reason we should expect gases to transmit applied pressure in all directions. When you inflate an automobile tire, pressure is applied at the valve stem to the air confined within the tire. Since all parts of the tire become equally hard, you can see that this pressure is *transmitted equally in all directions.*

What happens when external pressure is applied to confined liquids? A farm hand went to the well, filled a jug with water, inserted the stopper, and hit the stopper a sharp blow with the palm of his hand. The bottom fell out of the jug, much to his astonishment. Let us inquire what really happened. Figure 5–17 represents the jug filled with water. As the stopper was driven into the jug by the force of the blow, *its pressure upon the confined liquid was transmitted equally in all directions.* For convenience let us assume that the neck of the jug had an area of exactly

1 sq. in., and that 10 lb. of force were used in driving the stopper into the jug. That means that *every* square inch of the inside surface was subjected to a pressure of 10 lb., *in addition to the weight pressure*. If the bottom of the jug had an area of 40 sq. in., the total force acting upon it must have reached the astonishing total of 400 lb. The bottom of the jug was not strong enough to withstand such a great force.

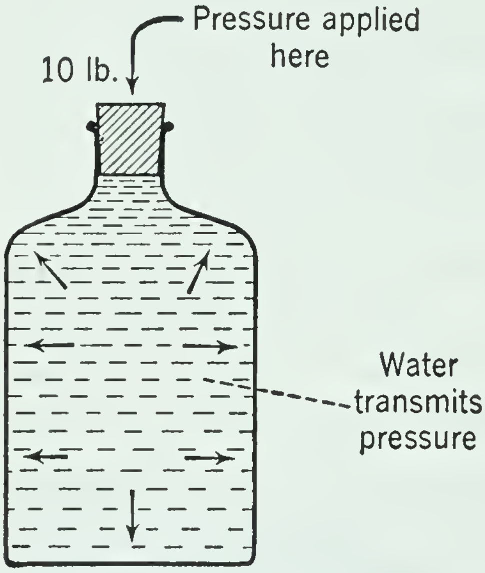


Fig. 5–17. Bottle to be used to demonstrate Pascal's law.

What is Pascal's law? The farm hand just mentioned had never heard of Pascal's experiments. Blaise Pascal was a French physicist who devised Pascal's vases to show that *weight pressure* of liquids is directly proportional to their depths, but independent of the shape of the container. But Pascal also devised an experiment to study the transmission of pressure by liquids when pressure from *outside* is applied to their surfaces. He fitted pistons in openings in the sides of a box filled with water, just like the cork in the jug of Figure 5–17. One opening had an area 100 times as large as the other and the pistons fitted the openings tightly. (See Fig. 5–18.) Pascal then found that *one man*, pushing against the small piston, could hold that piston against the force of *100 men* pushing against the large piston.

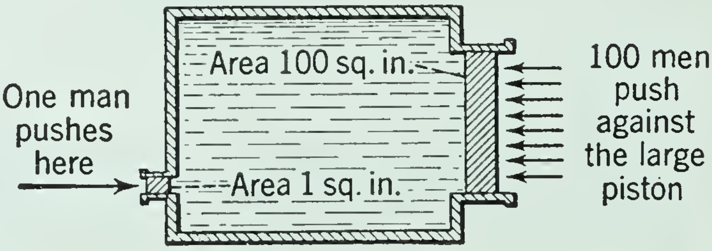


Fig. 5–18. How man can use a machine to multiply his feeble efforts.

His comment was: "Hence it follows that a vessel full of water is a new principle in mechanics, and a *new machine for multiplying forces* to any degree we choose, since one man will by this means be able to move any given weight."

This principle, which is known as PASCAL'S LAW, may be stated as follows: *Pressure applied anywhere to a body of confined or en-*

closed fluid is transmitted with undiminished force in every direction. This pressure acts at right angles to every portion of the surface of the container, with equal force upon equal areas. Both liquids and gases are fluids, so Pascal's law applies to both.

DEMONSTRATION. By means of a bottle-bursting apparatus similar to that shown in Figure 5–17, or a Pascal's syringe, demonstrate that a pressure applied to a confined liquid is distributed equally throughout the liquid.

B. THE HYDRAULIC PRESS

How is transmission of liquid pressure used to multiply force? From Pascal's law, we are led to the following conclusion: If A of Figure 5–19 has an area of 1 sq. in. and B an area of 100 sq. in., a weight of 1 lb. lying on the piston C will just balance a weight of 100 lb. on the piston D. A force *slightly* in excess of 1 lb. acting downward on the small piston will lift the weight of 100 lb. upon the large piston. From these observations, it is easy to see how it is possible to construct a mechanical device for multiplying force. If we make the large opening 1000 times the area of the small one, the small force on the small piston is multiplied by 1000.

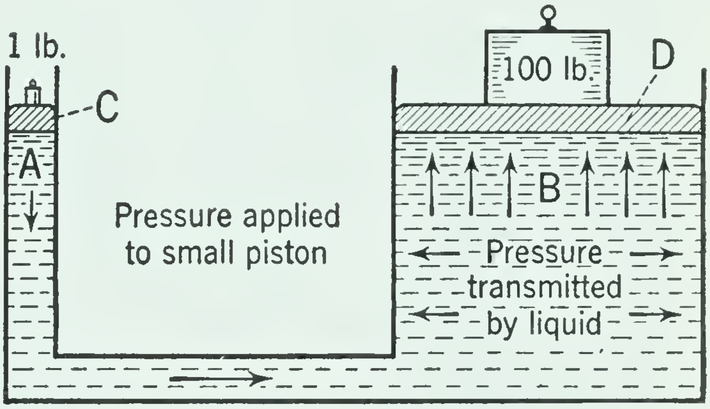


FIG. 5–19. Pressure applied to a confined liquid is transmitted equally in all directions.

We must never forget one important fact. As we *multiply force* by the use of any mechanical device, we diminish correspondingly the *distance and speed* of the load. In other words, *what is gained in force is lost in speed and distance.* Suppose we force the piston C down 10 in.; just 10 cu. in. of water will be forced from A into B. The 10 cu. in. of water that are forced into the large cylinder will spread out over an area of 100 sq. in. Therefore it will raise its level and lift the large piston $\frac{10}{100}$, or 0.1 in. In the time required for C to move 10 in., D moves only

0.1 in., just 0.01 as far as *C*. The force of 1 lb. is multiplied 100 times by this device, but the object to be lifted on the large piston moves 0.01 as fast as the force applied to the small piston. We have already learned (page 58) that in all mechanical devices, *the product of the acting force multiplied by the distance through which it moves equals the product of the resisting force multiplied by the distance through which it moves.* This is the *general law of frictionless machines.* Applied to this particular case, 1 lb. moving 10 in. is equivalent to 100 lb. moving 0.1 in.

How does the hydraulic press work? The commercial hydraulic press is an application of Pascal's law. By studying Figure 5–20, we may explain the operation of such a press. There are two cylinders, a small one and a large one. In each one there is a piston which fits so tightly that the liquid cannot be forced past it. A lever is attached to the small piston. As the small piston is pushed down, some of the oil or water from the small cylinder is forced over into the large cylinder *B*, and the large piston is lifted a trifle. As the lever is worked up and down, it continues to pump the liquid from the reservoir, and force it into the cylinder *B*. When the pressure is to be released, the valve shown in the diagram is opened to let the liquid flow from *B* back into the reservoir.

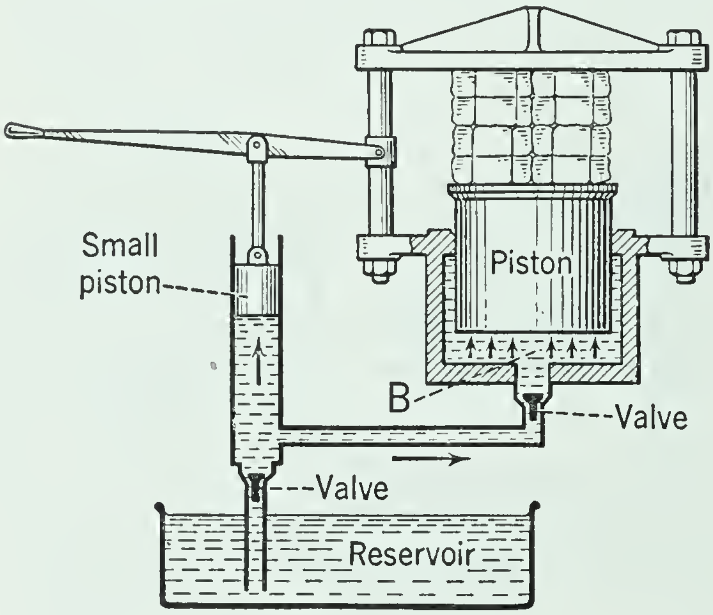


FIG. 5–20. The hydraulic press finds many uses.

1. DETERMINATION OF MA

Exclusive of the advantage of the lever, the mechanical advantage of the hydraulic press is equal to the area *A* of the large piston divided by the area *a* of the small piston. From your geometry, you learned that the *areas of two circles are proportional to the squares of their diameters.* Hence the formulas:

$$MA = \frac{A}{a}, \text{ or } MA = \frac{D^2}{d^2}$$

We may use the proportion:

$$E : R = a : A, \text{ or } E : R = d^2 : D^2$$

PROBLEM. A force of 500 lb. is applied to the small piston of a hydraulic press. Its diameter is 2 in. What resistance can be counterbalanced on the large piston, which is 40 in. in diameter?

Solution. The $MA = \frac{(40)^2}{(2)^2}$, or 400. If the machine multiplies the effort by 400, then 500 lb. of effort can counterbalance 400 × 500 lb., or 200,000 lb. Or, we may use the formula, $E : R = d^2 : D^2$. Therefore $500 : x = (2)^2 : (40)^2$. $x = 200,000$ lb.

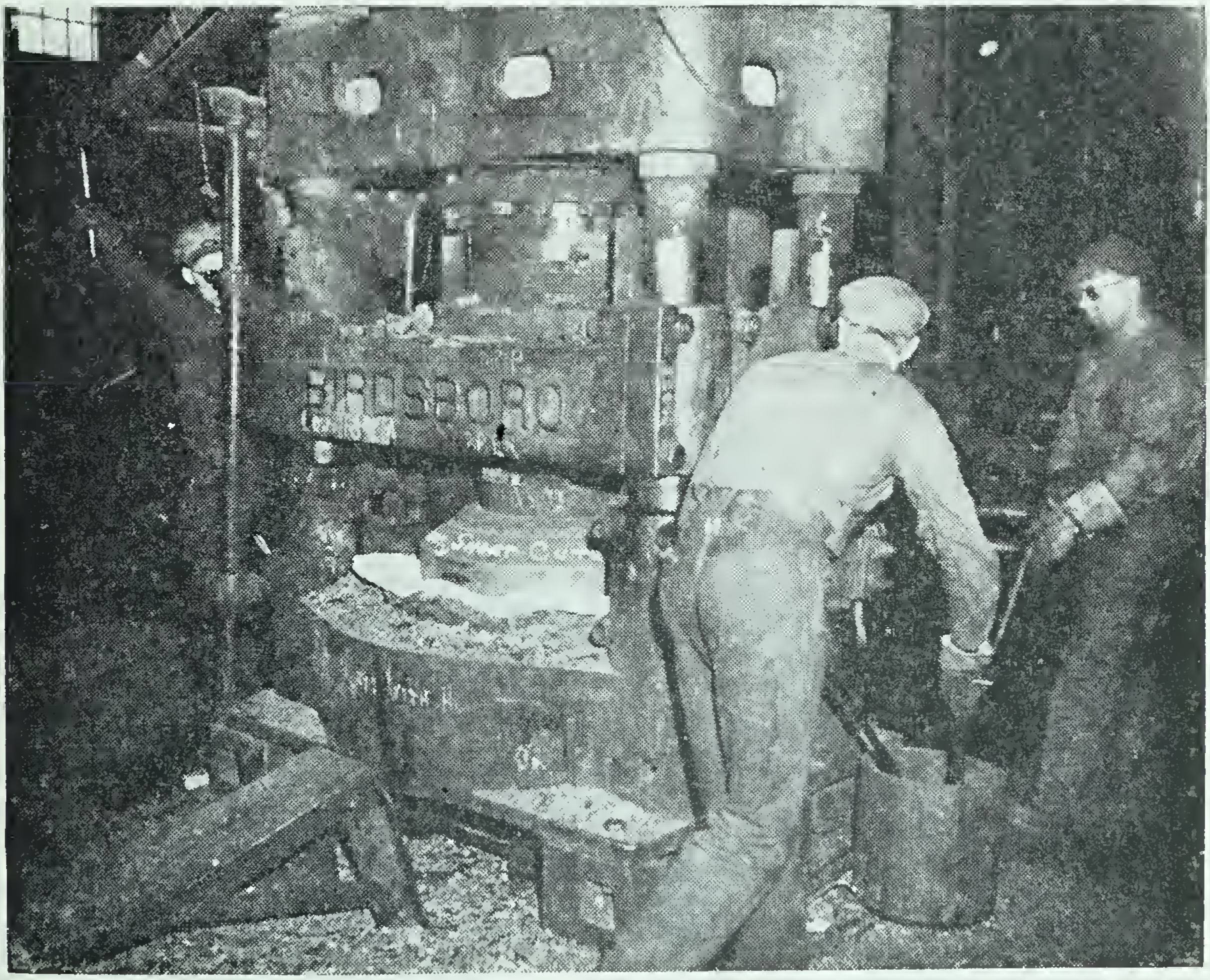


Photo by U.S. Army Signal Corps

FIG. 5–21. Under tons of pressure by the hydraulic press white hot steel plate is sheared in first operation in forging a 500-pound demolition bomb.

2. USES OF THE HYDRAULIC PRESS

The hydraulic press is used for baling cotton and paper, squeezing the juice from apples and other fruits, pressing oil out of seeds, punching holes in steel plates, embossing metals, and lifting enormous weights. (See Fig. 5–21.)

Demonstration. Use a model hydraulic press to show its action. Determine its mechanical advantage: (1) by means of the piston diameters, (2) from effort distance and resistance distances, and (3) from the effort and resistance.

C. HYDRAULIC BRAKES

How do hydraulic brakes work? Many automobiles are now equipped with hydraulic brakes, which are applications of Pascal's law. (See Fig. 5–22.) The force applied to the brake pedal acts upon a master piston from which it is transmitted through the oil in strong tubes to the brake piston. (See Fig.

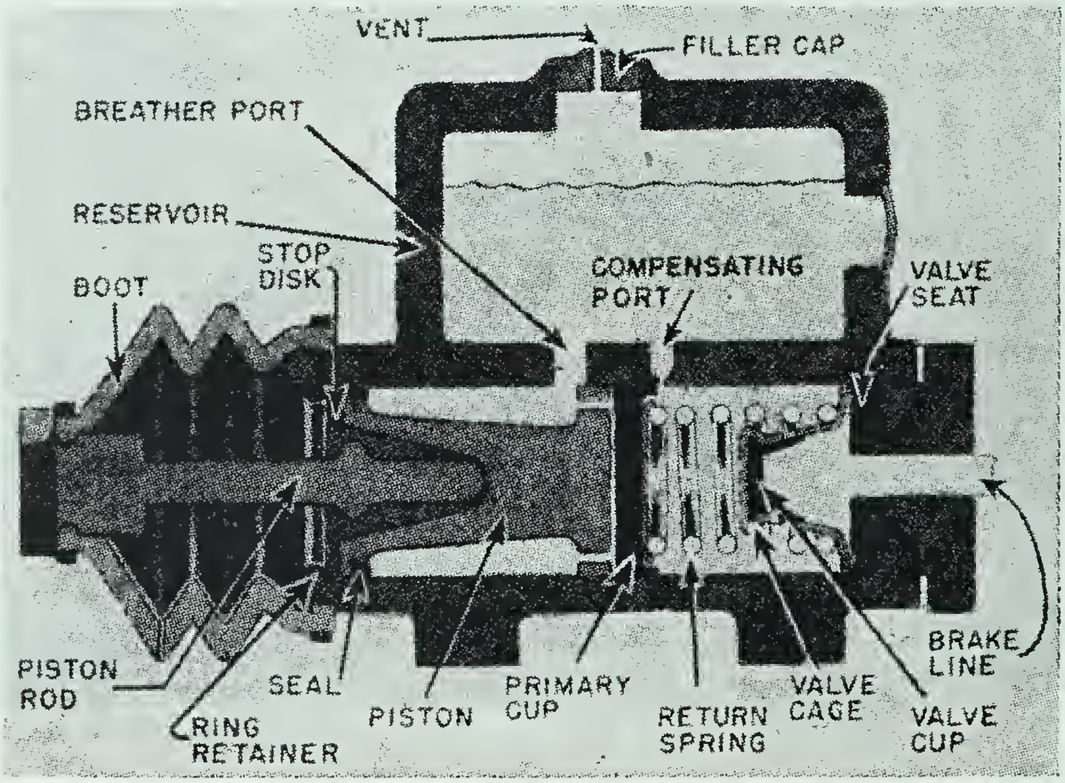


Fig. 5–22. Sectional view of master hydraulic brake cylinder.

5–23.) The pressure of the liquid in the brake piston pushes the brake shoes apart so that they will exert friction against the brake drum. A spring pulls the shoes together again when the brakes are released. If the pistons all have the same diameters, the pressure applied to the brakes on all wheels will be the same, and skidding is not likely. It is possible, too, to have the front-wheel brakes do a greater part of the braking, if desired. The newer cars follow this practice.

There are other applications of Pascal's law. Of course we are making use of Pascal's law when we inflate a tire. The *hydraulic jack* is used for lifting very heavy loads through a short distance. In many cases, dentists' and barbers' chairs are lifted by the use of hydraulic pressure. Hydraulic elevators operate by the use of water pressure acting upward on the bottom of a large piston beneath the elevator cage.

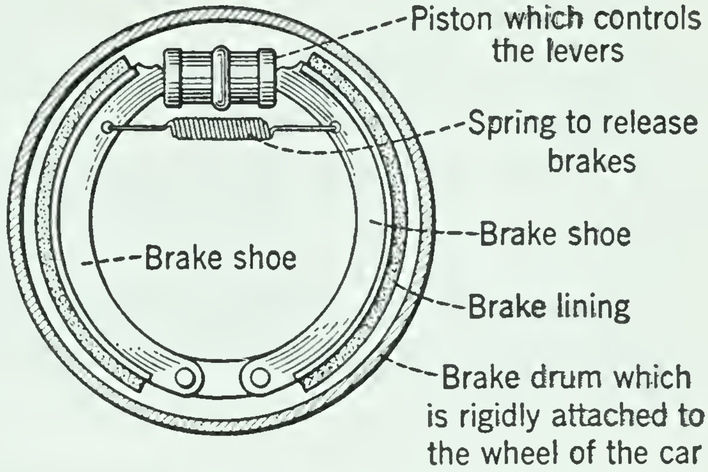

Piston which controls the levers
Spring to release brakes
Brake shoe
Brake shoe
Brake lining
Brake drum which is rigidly attached to the wheel of the car

Fig. 5–23. Some internal-expanding brakes operate by means of hydraulic pressure.

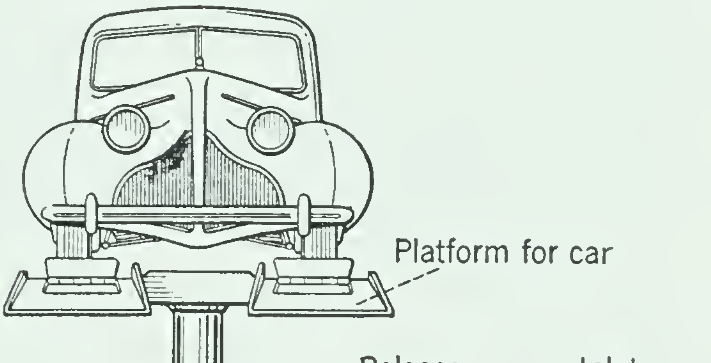


Fig. 5–24. The service station attendant uses Pascal's law to hoist a car and make work underneath the car more convenient.

The automobile hoist is a common application of Pascal's principle found at filling stations. (See Fig. 5–24.) Compressed air is applied to the surface of oil which then transmits the pressure to the lower end of the hoisting piston. In this manner a car weighing one or two tons can be hoisted easily.

Demonstration. Study the units of hydraulic brakes which may be obtained from an auto junk dealer, and outline the application of Pascal's law.

SUMMARY

1. Liquids have weight; therefore they exert pressure on the bottom and sides of the containing vessel.

2. Liquid pressure is directly proportional to the depth and density of the liquid and is independent of direction. Pressure caused by the weight of liquids is called gravity pressure.

3. The total force exerted upon any surface by a liquid equals the product of the area times the average depth times the density.

4. Pressure applied to any part of a confined fluid is transmitted with undiminished force in every direction. Such a pressure acts with equal force upon equal areas. This principle is known as Pascal's law.

5. Pascal's law finds application in the hydraulic press and various other devices.

6. The mechanical advantage of the hydraulic press is expressed by the formula:

$$MA = \frac{A}{a} \text{ or } MA = \frac{D^2}{d^2}$$

How many of the following terms can you define or explain?

Hydraulics
Pressure
Direct proportion
Inverse proportion
Total force
Gravity pressure
Pascal's law
Hydraulic press

SELF-TESTING EXERCISES

ANSWER THESE QUESTIONS

On a separate sheet of paper numbered from 1 to 4 write the letters for the phrases that answer the following questions correctly.

1. Which of the following statements is true about pressure? Pressure is measured in (*a*) pounds; (*b*) grams; (*c*) pounds per cubic foot; (*d*) grams per square centimeter.

2. Which of the following phrases correctly completes the statement: The total force produced by a liquid on the bottom of a container is equal to (*a*) the weight of the liquid; (*b*) pressure times the area; (*c*) density times area; (*d*) depth times density.

3. Which of the following terms correctly describes the method of causing pressure by the weight of liquids? (*a*) Standard pressure; (*b*) applied pressure; (*c*) gravity pressure.

4. If we multiply force by the use of any mechanical device, which of the following statements is true? (*a*) We increase efficiency; (*b*) we decrease efficiency; (*c*) we reduce friction; (*d*) we lose speed.

COMPLETE THESE STATEMENTS

On a separate sheet of paper numbered from 1 to 6 write the words needed to fill correctly the blank spaces in the following sentences.

The pressure which a liquid exerts is ..(1).. proportional to its depth. At a depth of 1 ft., the water pressure is ..(2).. lb. per sq. in. Liquid pressure is ..(3).. of direction. Pressure applied to a confined fluid is transmitted with ..(4).. force in ..(5)... The hydraulic press is an application of ..(6)...

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 6 write a T *or an* F *to show whether each statement is true or false.*

1. The pressure which a liquid exerts is inversely proportional to its density.

2. If the acting force is applied to the large piston of a hydraulic press, a mechanical advantage of speed may be obtained.

3. The total force on the bottom of a container may exceed the total weight of liquid in the container.

4. Pascal's law does not apply to gases.

5. The shape of a container has nothing to do with what pressure the liquid exerts.

6. The difference in levels in water above and below a dam is called a water head.

QUESTIONS

1. Explain why water flows down hill.
2. Why is it difficult to keep water out of cellars?
3. Does water flow faster from a tap in the basement than from a similar tap on the third floor? Explain.
4. Two types of standpipes are shown in Fig. 5–25. If the water stands at the same height in both, how do the pressures compare?
5. Should a dam be made thicker at the bottom or at the top? Give a reason for your answer.
6. Three Pascal vases are made like those shown in Figure 5–3. The area of the base is the same in all three cases. They are filled to the same depth with water. Compare the pressures in each case. How do you think the total force on the bottom in each case compares with the weight of the liquid?
7. How does your city get its water supply? Is the reservoir high enough to furnish sufficient pressure for fighting fires? (See Fig. 5–26.)
8. The pressure at the point of a phonograph needle may amount to several tons per sq. in. Explain how this is possible, since the reproducer weighs only a few ounces. Why does the heel of a woman's shoe sink so deeply into soft ground?
9. Why does a liquid exert pressure? Upon what factors does the intensity of liquid pressure depend? Of what factors is liquid pressure independent?
10. A dam is built across a river. Does the length of the river affect the total force of the water against the breast of the dam? Give reasons for your answer.
11. Do you think that

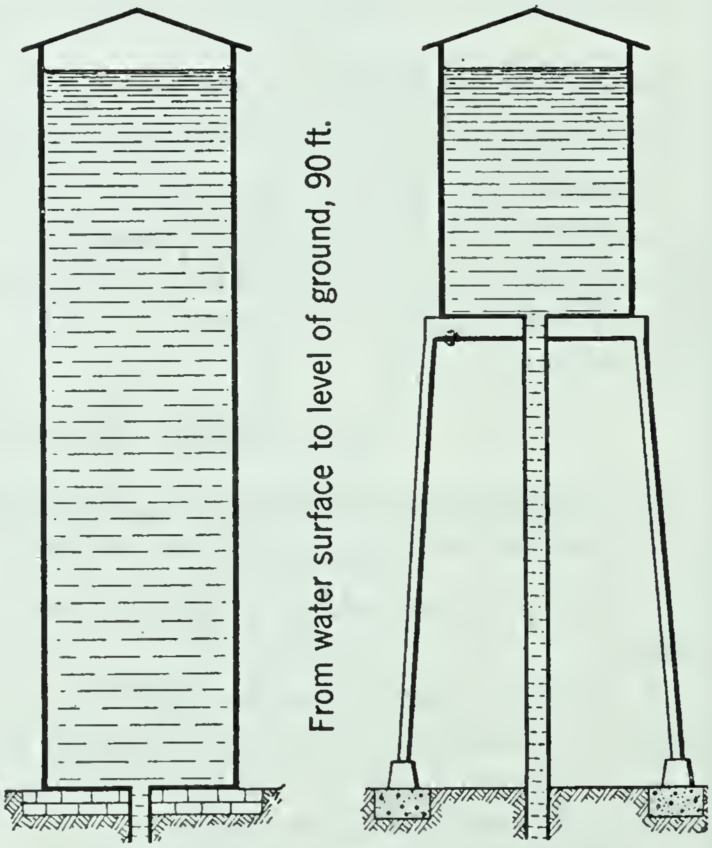
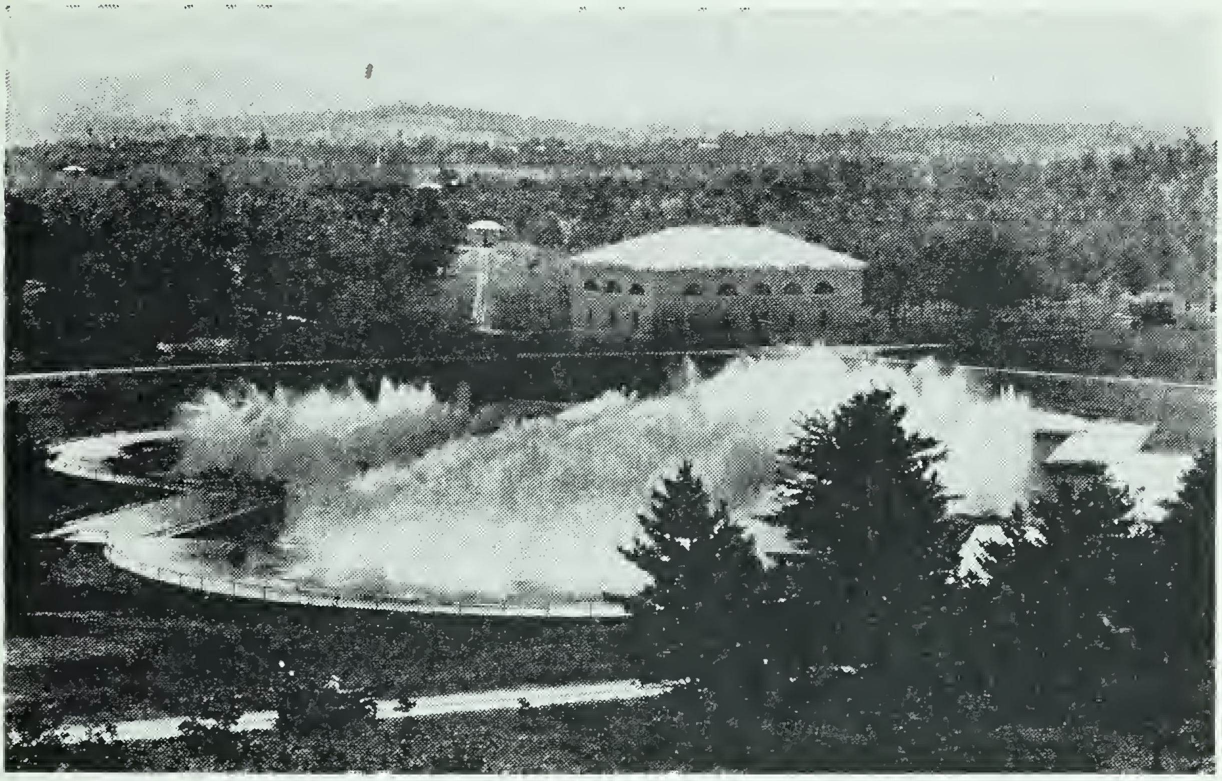


FIG. 5–25. Two types of standpipes.



Courtesy Board of Water Supply of New York City

FIG. 5–26. An aeration method of purifying water brought by huge pipes from a reservoir by exposing it in a spray to oxygen and sunlight.

there is any truth in the claim of manufacturers of hydraulic brakes that they are easily equalized?

12. Assuming that the story of the Dutch boy at the dike is true, how could he hold back the waters of the North Sea?

13. What would one gain by applying the acting force to the large piston of a hydraulic press and the resisting force to the small piston? (Use is made of this reversed application in launching airplanes from battleships.)

14. For sinking hostile submarines depth-bombs are used. They sink to a given depth before exploding. How does the transmission of liquid pressure make them effective in rupturing the walls of the submarine?

15. Why is the explosion of dynamite beneath the surface of water so destructive to fish?

16. Is it possible to have a mechanical advantage of speed? Explain.

17. A man bought a lawn roller which was to be filled with water to give it the necessary weight. When he screwed the end of his garden hose into the opening in one end of the roller and turned on the water, one end of the roller was pushed out. Explain.

18. Why is it a good idea not to fill a vacuum bottle entirely full of liquid before putting in the cork?

PROBLEMS

1. What is the pressure in gm. per sq. cm. of a column of water 4 m. high?

2. What is the pressure of a column of mercury 76 cm. high? (Density of mercury is 13.6 gm. per cc.)

3. How high a column of water will be needed to exert the same pressure as the column of mercury of problem 2?

4. A man dives into sea water (density is 64 lb. per cu. ft.) to a depth of 300 ft. What is the pressure upon each square foot of his body? On each square inch?

5. The surface of the water in a standpipe is 196 ft. above the level of a faucet. What is the pressure at the faucet?

6. What pressure is available when the water head is 500 ft.?

7. A tank 8 ft. long, 8 ft. wide, and 10 ft. deep is filled with water. Calculate the total force on the bottom of the tank.

8. Calculate the total force on one side of the tank of problem 7.

9. A vat 2 m. long, 160 cm. wide, and 1200 mm. deep is filled with sulfuric acid, density 1.8 gm. per cc. Calculate the total force on the bottom of the vat. Calculate the total force on one of the longer sides.

10. The elevation of the lake above Boulder Dam is 530 ft. above the surface of the river below the dam. What is the pressure at the base of the dam? Can you see why it is necessary to make the base of the dam of concrete 650 ft. thick? (See Fig. 3–2.)

11. The breast of a dam is 50 ft. long; its height is 40 ft. Find the total force against the dam when the water stands level with the top.

12. Some parts of the ocean are at least 30,000 ft. deep. What is the pressure at that depth? What would be the force upon your body assuming its area is 10 sq. ft.?

13. What is the mechanical advantage of a hydraulic press in which the area of the large piston is 500 times the area of the small piston?

14. What is the mechanical advantage of a hydraulic press if the diameter of the large piston is 15 times that of the diameter of the small piston?

15. The small piston of a hydraulic press has an area of 1 sq. in. The area of the large piston is 200 sq. in. What is the mechanical advantage of the press? What force must be applied to the small piston to balance a weight of 10 tons on the large piston?

16. The diameters of the two pistons of a press are 1 in. and 8 in. respectively. What force is needed to lift a weight of 144 tons?

17. The diameter of the inlet pipe of a hydraulic hoist is 1 in. The

piston has a diameter of 10 in. What pressure at the inlet must be used to lift a car weighing 4000 lb.?

18. By the use of a hydraulic press, 100 lb. must lift 40,000 lb. What mechanical advantage is needed? If the diameter of the small piston is 1 in., calculate the diameter of the large piston.

19. The two pistons of a hydraulic press have diameters of 2 in. and 30 in. respectively. If a force of 400 lb. is applied to the small piston, what load applied to the large piston can be lifted?

VI

Machines Utilize Properties of Molecules

A. MOLECULES MOVE

What is the kinetic theory of matter? We have learned that all matter seems to be made up of exceedingly small particles called molecules. In gases especially, we know that the molecules are not relatively near neighbors. In liquids and solids, they are more closely crowded, but in all cases there is ample room between adjacent molecules to permit the molecules to move freely. The word *kinetic* is derived from a Greek word meaning "to move." *The kinetic theory of matter assumes that the molecules of all matter are in constant motion.* The rate and nature of such motion depend upon the nature of the substance, its state, and its temperature. There are many evidences of the correctness of the kinetic theory.

1. THE BROWNIAN MOVEMENT

Molecules in motion. By the use of the ultramicroscope we can see how particles which are suspended in a liquid are driven forward and backward, or up and down, in ceaseless motion, by the impacts which they receive from moving molecules in the liquid. Try to imagine a soccer game in which you can see the ball but not the players. One player drives the ball across the field in one direction, another drives it back at a different angle, and then a third player drives the ball in a still different direction. In a similar manner a liquid molecule in motion collides with the tiny particle which you are watching. You see it driven forward by the force of the impact. Then, after it has traveled a short distance, it may be struck by another molecule moving in a different direction and have its path changed again. Thus we have the ceaseless dance of such particles as they are driven hither and thither. Because such motion was discovered by Robert Brown, a Scottish botanist, the name *Brownian movement* is given to this phenomenon. Minute oil drops suspended in air undergo the same zigzag movement as they are driven about by rapidly moving air molecules. Figure 6–1 represents a path that might be followed by such a particle.

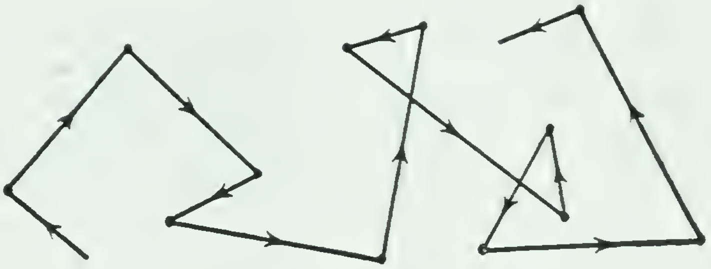


Fig. 6–1. The particle is driven hither and thither by the impacts of moving molecules.

Demonstration. With a microscope study the Brownian movement of carmine in water. Explain the motion of the microscopic particles.

Gases expand. If a gas cock is left open, in a few minutes the odor of gas may be detected in all parts of the room. If we unstopper a small bottle of chlorine gas in a large vessel of air, the yellowish green gas may be seen expanding and mixing with the air in the vessel. The gas molecules move rapidly in all directions until they become thoroughly mixed with the air molecules. Evidently the molecules of these gases are in very rapid motion. Air from the bell glass of Figure 6–24 expands instantly and fills the vacuum formed beneath the rising piston of the air pump. If the molecules of gases were not in constant motion, it would be impossible to produce a vacuum with an air pump. The expansion of gases furnishes one proof of the motion of their molecules.

Gases exert pressure. Pneumatic tires may burst from the pressure which the air inside exerts on the walls of the tire. This pressure is due to the constant bombardment of the tires by billions of moving molecules. If we pump three atmospheres into the space formerly occupied by one atmosphere, there will be three times as many molecules bombarding the walls of the container, and the pressure will be three times as great. From Figure 6–2 we see that tripling the number of molecules in a given space will triple the pressure because there will be three times as many impacts against the walls as before. An automobile driver uses a small pressure gauge to measure the force exerted by the molecules upon each square inch of the inflated tire. By Pascal's law, the pressure is transmitted equally in all directions. If one spot in the tire is especially weak, a "blow-out" is likely to occur. All the devices which utilize compressed air afford examples of gas pressure due to molecular motion. Steam in boilers often exerts a pressure of 200 lb. or more per sq. in. In this case it is also evident that the molecules are widely separated when compared with the diameters of the molecules themselves, for the water formed when steam condenses occupies about $\frac{1}{1700}$ the volume of the original steam. The high temperature increases the velocity of the steam molecules, and the rapidly moving molecules exert great pressure.

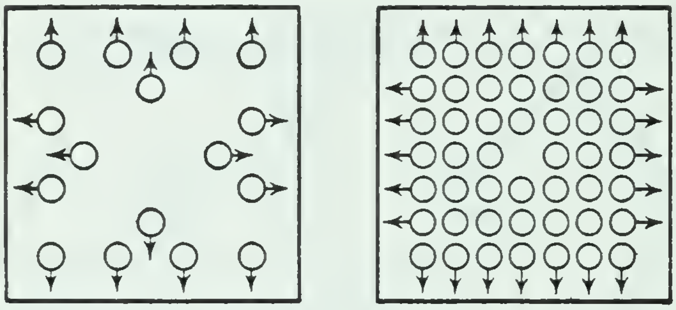


Fig. 6–2. Increasing the number of molecules in a container increases the pressure.

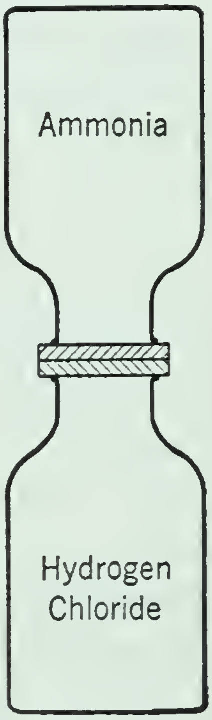


Fig. 6–3. Gases mix by diffusion of the moving molecules.

Diffusion of gases shows that molecules of gases are in motion. Hydrochloric acid is a water solution of a heavy gas, hydrogen chloride; aqua ammonia is a water solution of a light gas, ammonia. When these two gases unite, they form a cloud of fine white particles. Suppose that we put a couple of drops of hydrochloric acid in a warm bottle, an equal amount of aqua ammonia in a second bottle, cover both with glass plates, and then invert the bottle containing ammonia over the acid bottle, as shown in Figure 6–3. After the bottles have stood for a minute or two, a vigorous action may be observed when we remove the glass plates. The light ammonia gas moves *downward* and mixes with the heavy hydrogen chloride, and vice versa. The intermingling is apparently contradictory to the laws of weight. Other gases may be used, and they behave in the same manner. For example, carbon dioxide is about 22 times as dense as hydrogen, but if bottles of these gases are placed mouth to mouth, the hydrogen gas *above* and the carbon dioxide *below*, some of the molecules of the dense gas will move *upward* and mix with the hydrogen and some of the light hydrogen molecules will move *downward* and mix with the carbon dioxide. If the denser gas had been placed at the top, we could explain this phenomenon by the laws of weight, but since the gases moved in apparent violation of the laws of weight, it is quite evident that the molecules of gases are in motion. *Such intermingling of gases without regard to weight is called diffusion.*

DEMONSTRATION. How do two gases mix without forced circulation? Warm two wide-mouthed bottles by swinging them back and forth through a Bunsen flame. To one bottle add a few drops of ammonium hydroxide; to the other add a few drops of concentrated hydrochloric acid. Cover both with glass plates, and then invert the bottle containing ammonium hydroxide over the acid bottle. (See Fig. 6–3.) Allow the bottles to stand for two or three minutes. The heat of the bottles vaporizes ammonia gas (less dense than air) from the ammonium hydroxide and hydrogen chloride gas (denser than air) from the hydrochloric acid. Remove the glass plates, allowing the mouths of the two bottles to come together and the two gases to come in contact with each other. Note the white smoke produced. From the motion of the white smoke, do the two gases appear to mix? Explain.

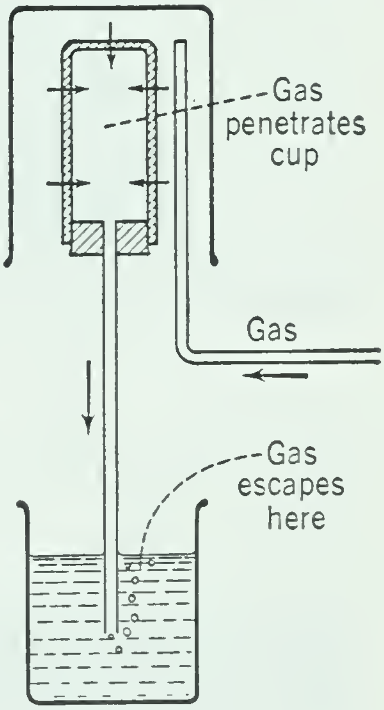


FIG. 6–4. Gases readily diffuse through porous solids. They also diffuse through membranes.

Gases diffuse through porous solids. In the apparatus shown in Figure 6–4, an unglazed earthenware cup is closed with a rubber stopper carrying a glass tube which dips into some colored liquid. When a beaker is inverted over the cup and illuminating gas is led into the beaker, air begins to bubble out through the liquid. This experiment shows that gases *diffuse* through a porous solid. It also shows that the lighter molecules of illuminating gas move faster than the denser molecules in the air. If a dense gas such as carbon dioxide is led into the beaker, molecules from the air flow out through the porous cup faster than the carbon dioxide molecules enter. This reduces the pressure inside the cup and the colored liquid rises in the tube. Such diffusion always takes place more rapidly from a less dense to a more dense medium.

Osmosis. The walls of membranes of both plant and animal cells allow gases to diffuse through them. Apparently this process is much the same as the diffusion of gases through the wall of an earthenware cup. The importance of such *diffusion of gases through a plant or animal membrane* can hardly be overestimated. The process is called *osmosis.* In ordinary breathing, the oxygen of the air passes through the walls of the capillaries in the lungs and enters the blood. It passes through the cell walls in the same manner. Osmosis also occurs in plant tissues. By osmosis, carbon dioxide enters the cells in the leaves of plants. Without osmosis, plant and animal life would cease to exist.

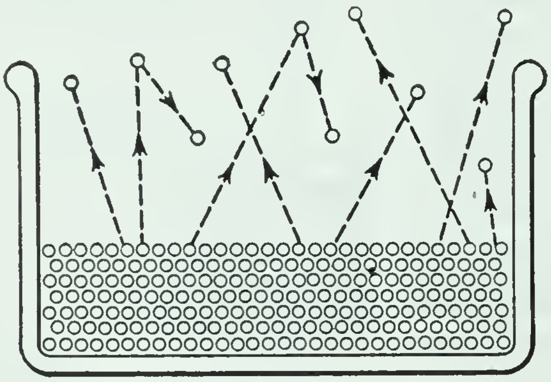


Fig. 6–5. Moving molecules escape at the surface of a liquid.

Why do liquids evaporate? Everyone knows that water left standing in an open vessel soon disappears by evaporation. It seems to be quite impossible to explain such disappearance of liquids, unless we assume that the molecules of the liquid are in motion. In Figure 6–5, we may picture what we believe to be constantly taking place in a liquid. The molecules move in all directions. Only those moving upward can escape into the air. Those that collide with air molecules may rebound into the liquid again. Exhausting the air above the liquid prevents such collisions. We can see from this why liquids evaporate more rapidly in a vacuum.

Visitors at the 1933 Century of Progress Exhibition in Chicago saw small steel balls thrown about violently by the bombardment of rapidly moving molecules at the surface of heated mercury.

Diffusion of liquids is slower than that of gases. Let us pour into a tall cylinder enough concentrated copper sulfate solution to form a layer of blue liquid two or three inches deep. Float a flat cork on the surface of the copper sulfate solution. We can then pour water carefully through a funnel tube on top of the cork so that it will spread out over the surface of the blue liquid, forming two distinct layers, since the water is much less dense than the solution of copper sulfate. (See Fig. 6–6.)

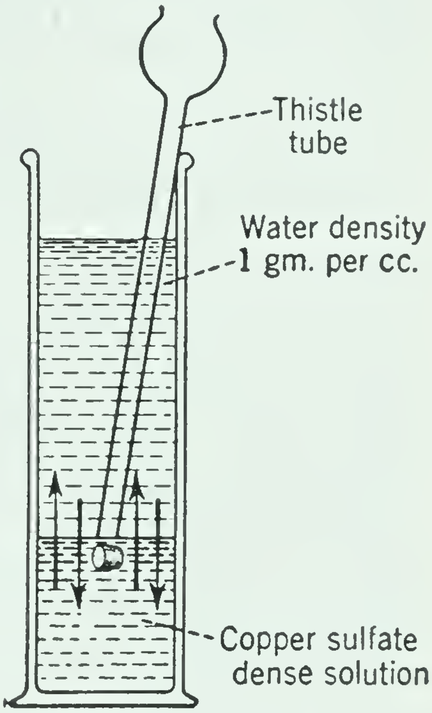


Fig. 6–6. Liquids diffuse more slowly than gases do.

After this cylinder stands a few days, the line of demarcation becomes quite irregular. Some of the blue solution moves upward and mixes with the water above, and some of the water molecules move downward into the copper sulfate solution. This experiment shows that diffusion also occurs in liquids. It may require weeks or months before the diffusion is complete, whereas diffusion between gases is complete in a few minutes. This experiment shows that the molecules of liquids are in motion, but that they move much more slowly than the molecules of gases.

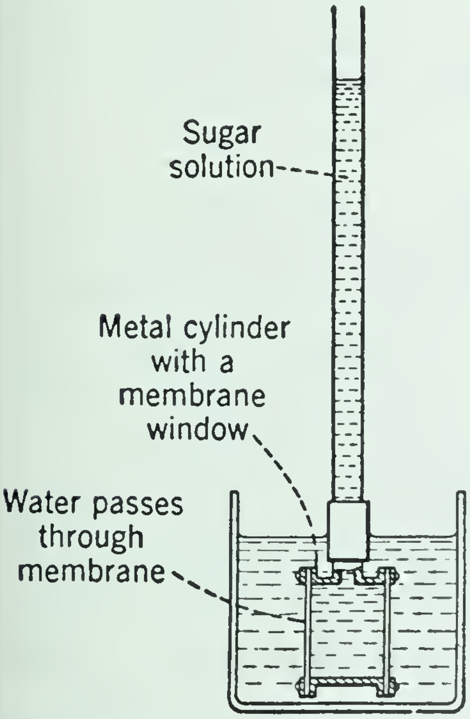

Sugar solution
Metal cylinder with a membrane window
Water passes through membrane

Fig. 6–7. Liquids pass through membranes by osmosis.

Does osmosis occur in liquids? The apparatus shown in Figure 6–7 may be used to show that liquids diffuse through membranes. The diffusion apparatus and the attached tube are partly filled with a colored sugar solution of 1% or 2% strength. The shell is then immersed in a vessel of water. In a few minutes the liquid begins to rise in the tube, and by the following day it will probably have reached a height of several feet. The light water molecules move much more rapidly than the sugar molecules, and for that reason their penetrating power is greater. In the osmosis of liquids, the *diffusion takes place from the less dense to the more dense liquid.* The pressure produced by the osmosis of liquids may equal several atmospheres.

Osmosis of liquids is quite as important as that of gases. The purpose of digestion is to render the food sufficiently fluid to be absorbed by osmosis. Each cell receives its nourishment by osmosis through the cell wall. The mineral matter in the soil dissolves in the water and enters the root hairs of plants by diffusion. Thus plants depend upon osmosis for nourishment.

Solids evaporate. The fact that solids evaporate is not so well known, but a little thought must convince us that solids do evaporate, although in most cases very slowly. A piece of musk will give off enough vapor to be perceived in any part of the room. A lump of camphor gum or a crystal of iodine will disappear in a short time by evaporation. Moth balls evaporate completely in time. Snow and ice evaporate quite readily. They disappear when it is too cold for them to melt. It is probable that many other solids evaporate, but so slowly in many cases that it is hardly noticeable. Thus the evaporation of solids furnishes evidence that their molecules are in motion. It is difficult to see how any solid can have an odor unless its molecules escape by evaporation.

Diffusion of solids is very slow. If a lead plate and one of gold are left in close contact for a long time, particles of gold may be detected throughout the lead, showing that solids diffuse. The action is so slow that months are needed to produce even a slight diffusion. Other solids show a similar effect if the temperature is increased a few hundred degrees. From the evaporation and diffusion of solids, it is evident that molecular motion exists, even in compact, dense solids.

Demonstrations. 1. Does diffusion take place in liquids? Into the bottom of a graduated cylinder pour some concentrated copper sulfate solution by means of a thistle tube. (See Fig. 6–6.) Let it stand for two or three days. Is there any visible evidence of the denser copper sulfate solution and the lighter water mixing? Explain.

2. Place a ball of naphthalene (moth ball) on a watch glass. Note the size of the ball. Observe again after four or five days. Explain the change in size. Does this represent diffusion or evaporation, or both? Give a reason for your answer.

B. MOLECULES ATTRACT ONE ANOTHER

1. COHESION

Attraction among like molecules. Since there is so much evidence in support of the kinetic theory of matter, you probably wonder why all substances do not evaporate rapidly and expand indefinitely. Instead, we know that many solids have great tensile strength, and that enormous forces are required to pull them apart. In spite of the molecular motion, there seems to be a strong force binding together the molecules of such tenacious solids. *This force of attraction between like molecules is called cohesion.*

2. ADHESION

Attraction among unlike molecules. *Unlike* molecules sometimes *adhere* to one another strongly. Tar sticks to our shoes, glue sticks to wood, and the dextrine on a postage stamp makes it adhere to an envelope. When we write on the blackboard some of the particles of the crayon adhere to the board. Writing with a "lead" pencil would be impossible if the molecules of the graphite of which the pencil is made did not adhere to the paper more strongly than they stick together. *The force of attraction between unlike molecules is called adhesion.*

Demonstrations. What are some evidences of attraction between molecules?

1. Pour a few drops of mercury into a beaker. Note how it breaks into small beads. Explain. Why does the mercury not "wet" the glass?

2. Moisten two ground-glass plates of the same size with water and press them together. Try pulling them apart. Explain.

3. Press two freshly cut edges of lead together and try to separate them by pulling. Is the force you find cohesive or adhesive?

C. COHESION AND ADHESION IN SOLIDS, LIQUIDS, AND GASES

Compare solids, liquids, and gases. Generally, the force of cohesion in solids is very great. The moving molecules are so firmly held by this force that they probably oscillate about fixed points, and do not change their relative positions to any marked degree.

In such liquids as tar and molasses, it is evident that the force of cohesion is considerable. In such mobile liquids as water and alcohol, the cohesion is much less, although still measurable. While in liquids the force of attraction between molecules exceeds the effect due to molecular velocities, yet the difference is so small that liquid molecules readily slide over one another; thus the liquid takes the shape of the container.

In gases, cohesion is very feeble, and molecular motion so evident that the molecules of gases actually *appear* to repel one another. The force of cohesion is so small that it does not prevent gases from expanding indefinitely.

It seems apparent that the state of matter depends upon the balance between molecular forces and molecular velocities. In a bar of steel, cohesion is exceedingly great and molecular velocity seems small. If we warm that piece of steel, its molecules move faster, and its strength is diminished. If we continue to raise its temperature, a point is finally reached where the steel becomes liquid. Its molecules then slide over one another like those of water. At still higher temperatures, steel becomes a vapor, and has the properties of gases.

1. COHESION AND ADHESION IN SOLIDS

Elasticity depends upon cohesion. From the preceding section it is easy to see that the tenacity, or tensile strength, of a substance depends upon the cohesion of its molecules. Several other special properties of matter, such as ductility, hardness, and malleability, depend upon cohesion. The elasticity of solids is also dependent upon this force.

It takes a certain amount of force to stretch a rubber band. When the distorting force is removed, the rubber band tends to resume its original length. Such a band is said to be *elastic,* and that type of elasticity which is exemplified by the stretching of a rubber band is called elasticity of *extension* or *traction.* Engineers use the term "stress" in speaking of a force which acts upon a body and tends to distort it. The change produced or the distortion is called "strain." If we squeeze a tennis ball, it becomes distorted, but it tends to recover its original form and size when the stress is removed. This is an example of elasticity of *compression.* A golf ball struck by a club is compressed before it begins its flight. The twisting of a coiled spring is an example of elasticity of *torsion.* The elasticity of *flexion* or *flexure* is exemplified by the bending of a strip of steel. In all these cases the body tends to resume its original form when the stress is removed.

How is elasticity measured? Usually when we speak of an elastic object, we mean one which is easily distorted, such as rubber. Engineers use the term "elasticity" in a different sense. Steel is said to be highly elastic, because it requires a great force to cause its deformation. Steel has a high *elastic constant.*

Suppose that we have two wires of different material, but of the same cross-sectional area. If it requires twice as much stress to stretch the first a certain distance as it does to stretch the second the same distance, the former has an elastic constant twice as high as the latter. In this sense steel is the most elastic substance known. Rubber has a very low elastic constant.

What is perfect elasticity? If we stretch a coiled spring, it *may* return exactly to its original form after the removal of the stress. (See Fig. 6–8.) If it does, it is said to be *perfectly elastic.* If we stretch such a spring too far, it remains permanently distorted. We have exceeded its *elastic limit.* Every material has a certain range of perfect elasticity through which it may be distorted before its elastic limit is reached. For example, it takes a great force to stretch a steel wire, but it cannot be stretched very far without becoming permanently distorted. Its *elastic constant* is high, but its *elastic limit* is low.

Liquids are perfectly elastic and they have a high elastic constant. Gases have a low elastic constant, as we find if we consider Boyle's law. They are, however, perfectly elastic. With both liquids and gases, we are concerned with elasticity of compression *only.* Within the limits of perfect elasticity, the elastic constant of any substance equals $\frac{\text{stress}}{\text{strain}}\cdot$ *Stress is the acting force and strain is the change produced.*

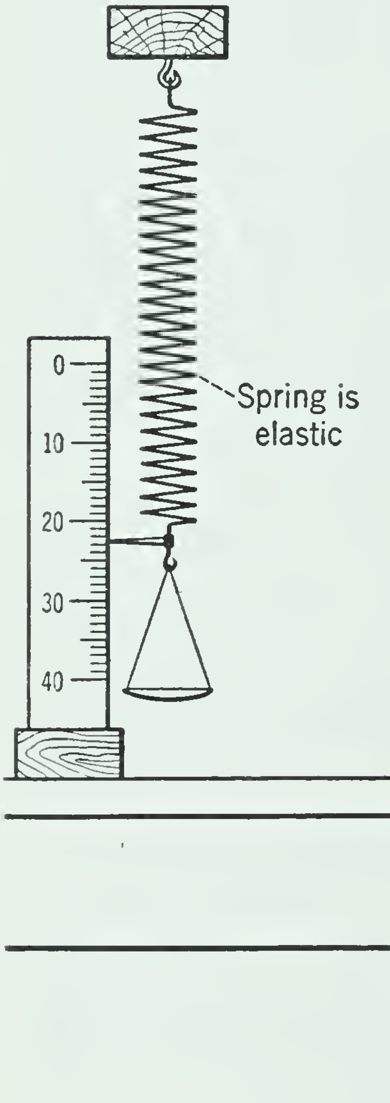


FIG. 6–8. Elasticity of extension in a coiled spring.

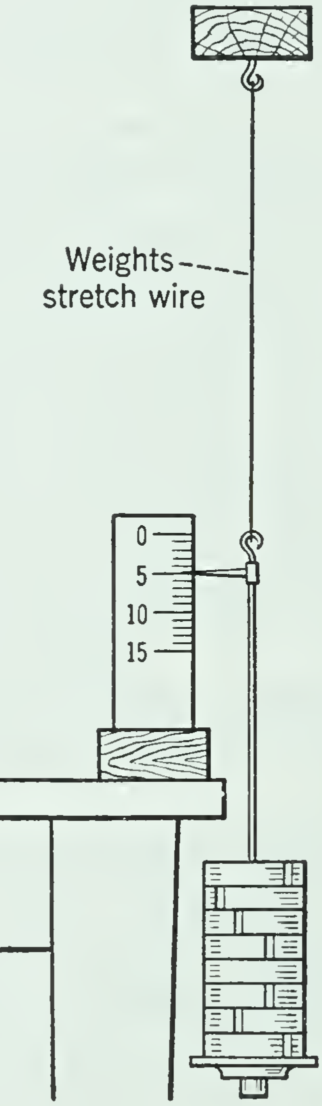


FIG. 6–9. Testing the tensile strength of a wire.

What is Hooke's law? If we fasten one end of a wire to a beam, and add weights to the hanger attached to the other end, the wire will be gradually stretched as weights are added one by one. (See Fig. 6–9.) Suppose we find that a weight of 100 gm. stretches the wire 1 mm.; then 200 gm. will stretch the wire 2 mm.; 300 gm., 3 mm.; and so on, until the elastic limit is reached. By such methods Hooke found that distortion is proportional to the distorting force or, in general, *distortions of elastic material are directly proportional to the distorting force, provided the elastic limit is not exceeded.* HOOKE'S LAW may be briefly stated as follows: *Within the limits of perfect elasticity, strain is directly proportional to stress.*

The spring balance is a common example of this law, since the 1-oz. divisions are equidistant.

Demonstration. For a given spring, is the change in length the same for each additional unit of weight? Suspend a small pan from the lower end of a coiled spring and fasten a ruler or meter stick in a vertical position beside the spring. (See Fig. 6–8.) Place small weights one at a time in the pan. Note the centimeter reading on the vertical scale after the addition of each weight. Add weights until the elastic limit is reached. Calculate the amount of displacement for each gram of weight added. How do these figures compare? Are they in agreement with Hooke's law? State the law.

What is the law of rebound? If we throw an elastic object against a hard surface, it rebounds. As a batted ball comes toward him, the shortstop on a baseball team must be able to judge the angle which it will make with the earth, the point at which it will strike the ground, and the angle at which it will rebound. If his judgment is accurate, he can then place his hands in position to catch the ball as it rebounds. In Figure 6–10 let the horizontal line represent the ground and O the point at which the ball hits the ground. Suppose that we erect a perpendicular OC at O. The line AO shows the path of the ball, and OB the line along which it rebounds. If the ball is perfectly elastic and the surface hard, the ball will rebound so that the angle BOC, or the angle which the line of rebound makes with the perpendicular, is exactly equal to the angle AOC, or the angle that the line along which the ball was batted makes with the perpendicular. *The angle of rebound, BOC, is equal to the angle of incidence, AOC.* In such games as tennis, basketball, and billiards the player is constantly making use of this *law of rebound.*

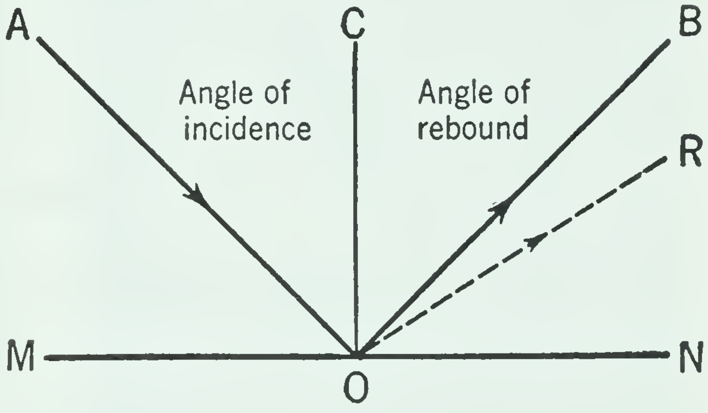


Fig. 6–10. Angle of incidence and angle of rebound are equal.

When a ball that is not perfectly elastic, a dead tennis ball for example, is driven against a hard surface, the angle of rebound, *ROC*, is greater than the angle of incidence. Uneven surfaces and balls that have lost some of their elasticity are responsible for many errors in baseball and tennis.

There is one exception to the law of rebound. A ball spinning on its axis as it moves does not rebound as shown in Figure 6–10. A tennis ball that is "cut" to make it rotate is harder to handle, since the player who receives cannot judge the rebound. Of course, a ball that is spinning does not travel along a straight line, but along a curve.

How can we find strength of materials? It is very important for builders to know the coefficient of elasticity of structural materials. It is just as essential for engineers to know the breaking strength of the materials which they use. In physical-testing laboratories, strong machines are used to measure the strength of materials. Such machines test the tensile strength of cables, ropes, wires, and belts. Tests are made of the compression strength of materials used for piers, pillars, posts, and foundations, which must not be crushed by the load which they are required to sustain. The propeller shaft of a steamship and the power shaft of an automobile must transmit power without the twisting of the shafts themselves. A General Motors exhibit at the Century of Progress Exhibition enabled one to measure in millionths of an inch the amount he could bend a piece of standard steel rail by pressure with his fingers. Several types of beams have been designed to give great strength without undue increase in weight. Figure 6–11 shows some of the types that are very much used by structural engineers.

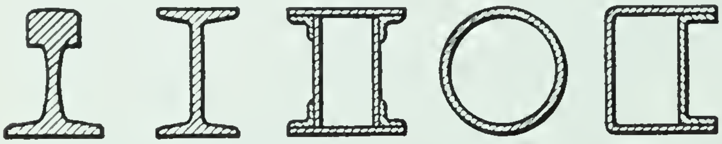
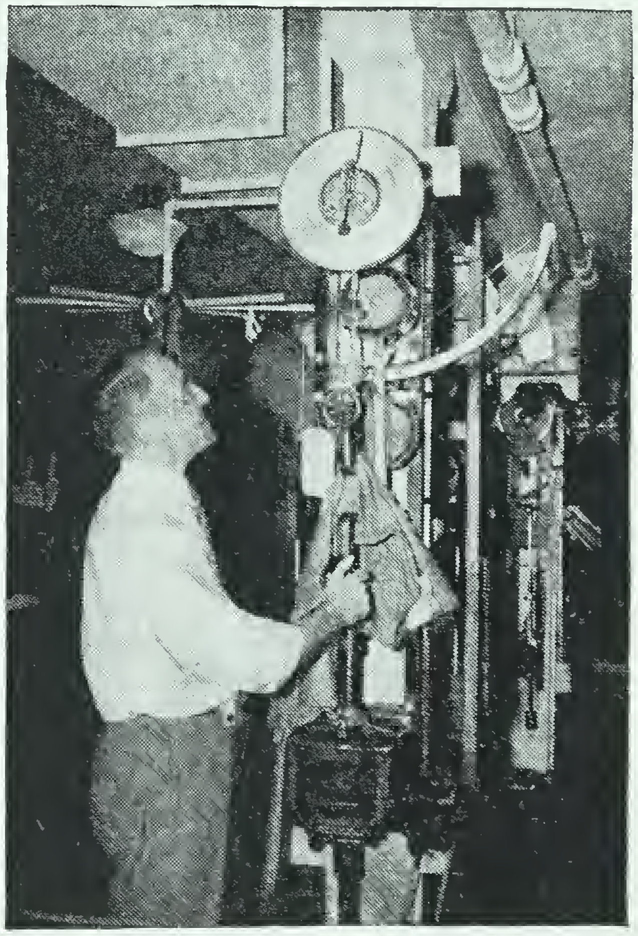


FIG. 6–11. T-rail and beams of various types in cross-section.

When designing machines or structures of any kind, engineers always plan to use materials heavy enough to carry several times the load that is likely to be put upon them. This gives a *factor of safety*, for it provides for flaws in the material and for temporary overloading. A bridge which is made of material heavy enough to carry 50 tons is said to have a safety factor of 5, if its load is limited to a capacity of only 10 tons. Six cables were used to lift the elevators to the top of the 624-ft. observation tower of the Sky Ride in Chicago, although one cable was strong enough to carry the load. That furnished a safety factor of 6. Various fabrics are frequently tested for strength just as structural materials are tested. (See Fig. 6–12.)



Courtesy of U. S. Army Signal Corps

FIG. 6–12. A fabric-breaking machine being used to test the strength of Army fabric.

DEMONSTRATION. Set up an apparatus similar to that shown in Figure 6–9. Place a box just beneath the weights so that they will fall only a short distance when the wire breaks. Using an iron wire No. 30 (or smaller) add weights until the wire breaks. Note the total weight necessary to break the wire. Repeat, using copper and aluminum wire of the same diameter. How do the three breaking strengths compare? By means of a vernier or a micrometer caliper measure the diameter of the wire used. From the known diameter and the breaking strength in each case, calculate the tensile strength of each of the substances, on the assumption that it varies directly with the cross-sectional area, and compare these computations with the values listed for these metals in Appendix A.

2. COHESION AND ADHESION IN LIQUIDS

There are molecular forces in liquids. If you stick a finger into thick molasses and then withdraw it, you are conscious of a certain amount of force needed to pull apart the molecules of the molasses.

By use of the following experiment, it may be shown that some force is necessary to overcome the cohesion of water molecules. Let us attach a glass plate to one pan of a balance and counterpoise it. Next we shall place a jar of water under the glass plate so that the lower surface of the plate just touches the surface of the water. We may now add several small weights in order to lift the plate. (See Fig. 6–13.) Since the plate is wet when pulled away, the additional weights must have been used to tear the water molecules apart. The adhesion of the water molecules to the glass is greater than their cohesion for one another; hence water wets glass.

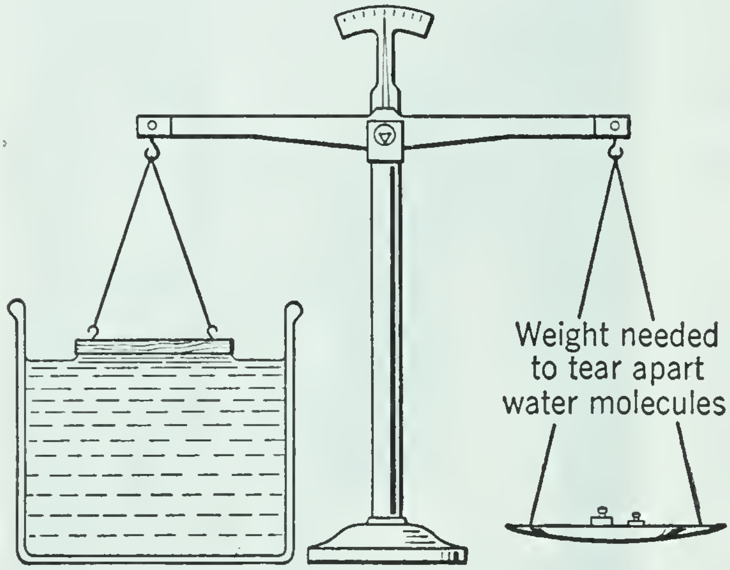


Fig. 6–13. Cohesion of water molecules is measurable.

If mercury had been used instead of water, the glass would not have been wet by the mercury, since the cohesion of mercury molecules is greater than their adhesion to glass. For the same reason, mercury does not wet the finger when it is dipped into a bowl of mercury. The force of cohesion varies in different liquids. It is less than in solids, but it is fairly strong in some *viscous* liquids.

What are surface tension and liquid films? Nearly everyone has seen someone float a small sewing needle or a safety-razor blade on the surface of a glass of water. The needle is more than seven times as dense as the water. A careful examination of the water surface shows that the needle floats in a little hollow in the water surface. *The water behaves as if a thin elastic film or membrane had been stretched over its surface.* This property of liquids is called *surface tension.* The weight of the needle is not great enough to break this liquid film. A wet needle cannot be floated in this manner; hence this experiment is more easily performed if the needle is first covered with a film of oil.

Small insects can run around over the surface of the water, since their weight is not great enough to break the surface film. All liquids are like water in this respect. In alcohol, the film is not so strong as in water.

What is viscosity? Many liquids, such as lubricating oils, have weaker surface films than that of water but have more friction within the liquid itself. Such liquids pour slowly and are called *viscous* liquids. (See page 5.)

Engineers test the viscosity of lubricating oils by counting the number of drops which will pass through a tiny opening in one minute. For comparison, several glass tubes may be filled with oils of different viscosity. Their relative viscosities are compared by noting the relative time needed for steel balls of equal weight to fall through the oils in the tubes. A high-viscosity oil is thick and flows slowly; a low viscosity oil is thin and flows freely. Refiners designate various viscosities of oils by a series of SAE (Society of Automotive Engineers) numbers such as S.A.E. 20, S.A.E. 30, and S.A.E. 40; the higher the number the more viscous the oil.

DEMONSTRATIONS. 1. Obtain three or four samples of lubricating oils of different S.A.E. ratings. In the bottom of a tin can drill a hole just large enough to allow a sample of the most viscous oil to drip slowly. Fill the can with the most viscous oil at hand and count the number of drops which pass through in two minutes. Repeat for all the other samples, making sure that the can was filled to the same level in each case. Compare the results with the S.A.E. numbers of the samples.

2. By means of forceps or a loop of wire lower a razor blade to the surface of water in a beaker. Cut a small square of fine wire mesh. Turn the edges up in the shape of a boat or shallow box and gently lower to the surface of water in a beaker. Do these objects float or sink? Explain. Fill a wide-mouthed bottle with water and tie a piece of cheesecloth over the mouth. Invert the bottle. Does the water flow through the cloth? Explain.

Liquid films are elastic. If we blow a soap bubble and then remove the pipe from the mouth, the bubble slowly contracts, forcing the air out of the pipe-stem. (See Fig. 6–14.) A film of soap will slide the looped wire along the frame of Figure 6–15 as it

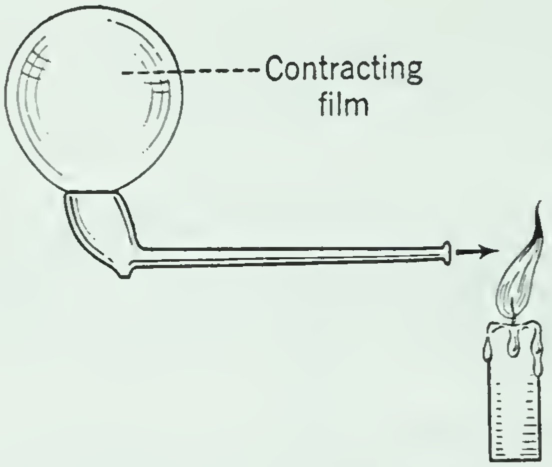


Fig. 6–14. Film contracts and expels part of the air.

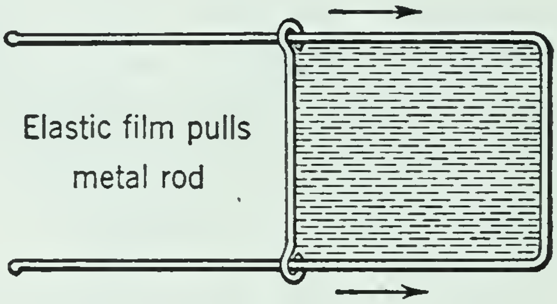


Fig. 6–15. Liquid film is elastic and contractile.

contracts. When we dip a wire ring containing a loop of thread, Figure 6–16A, into a dish of strong soapsuds, a film is formed across the ring. If we break the film inside the loop with a hot wire, the unbroken film outside the loop contracts and pulls the thread into the form of a circle, as in Figure 6–16B. These experiments show that the *surface films of liquids are elastic.* Since this film contracts to make the surface as small as possible, the tendency of liquid films to contract is often called the *surface tension of liquids.*

Reference to Figure 6–17 aids in the explanation of surface tension. A molecule at A is attracted equally in all directions by the cohesion of the surrounding molecules. A molecule at B is attracted laterally and downward, but not in an upward direction. Thus there

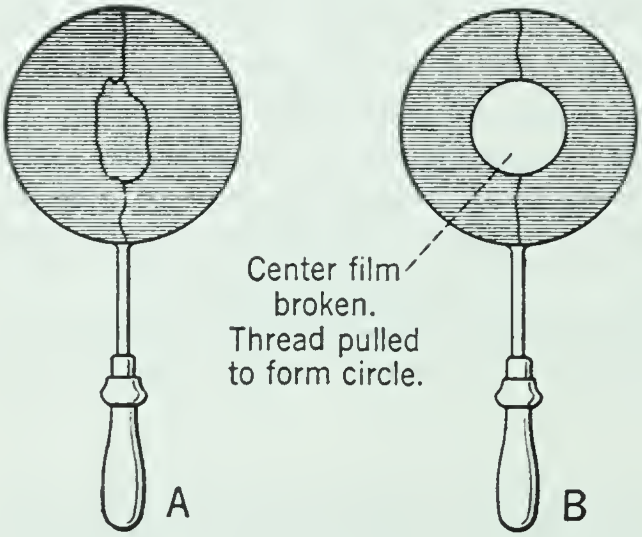


Fig. 6–16. A. Soap film is formed. B. Soap film contracts and pulls loop of thread into circle.

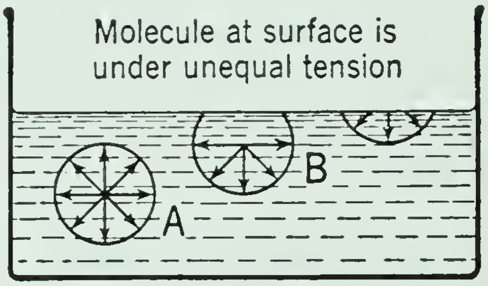


Fig. 6–17. Any molecule at the surface is under uneven tension.

is exerted upon the surface molecules an unbalanced force tending to pull them toward the interior of the liquid. This unbalanced, contractile force causes the surface to act like an elastic membrane.

What is the shape of liquid surfaces? A careful examination of the surface of the water in a glass container shows that it is not *exactly level* but that it is *slightly concave.* The edge of the surface where it comes into contact with the glass is lifted a little above the general level. (See Fig. 6–18*A*.) This crescent-shaped surface of a liquid column is called the *meniscus.* In reading the height of the water surface in a graduated glass cylinder, we read to the *lower part* of the meniscus, since the actual volume of liquid lifted above this level is small. The reason for the lifting of the water at the edge is explained by the fact that the *adhesion* of the water for the glass is greater than the *cohesion* between the water molecules.

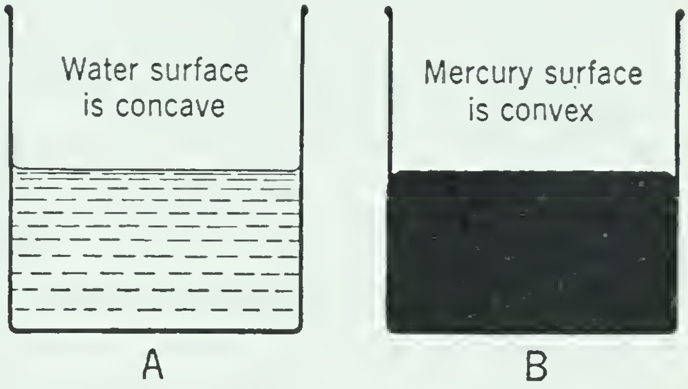


FIG. 6–18. *A*. Liquids which wet the surface of their containers have concave surfaces. *B*. Liquids that do not wet vessels have convex surfaces.

When mercury is used instead of water, the edges of the liquid are depressed and the surface is *slightly convex.* In this case the cohesion between the mercury molecules is greater than their adhesion for the glass. (See Fig. 6–18*B*.) In reading the height of a mercury column, one reads to the *top* of the meniscus.

What shape does a free liquid assume? When we speak of a free liquid, we mean a liquid that is not subjected to any force or pressure. A little water poured upon the floor is not a free liquid. Under the influence of gravity, the water spreads out in all directions, since its molecules slide over one another readily. Raindrops are nearly spherical; they are common examples of free liquid. If we fill a glass cylinder half full of water, and then float a layer of alcohol on the surface of the water, we can lower a drop of oil into the liquid and find that we have practically nullified the force of gravity. The oil is denser than the alcohol, but not so dense as the water. Hence it floats in the mixture. *Its shape is spherical.* (See Fig. 6–19.)

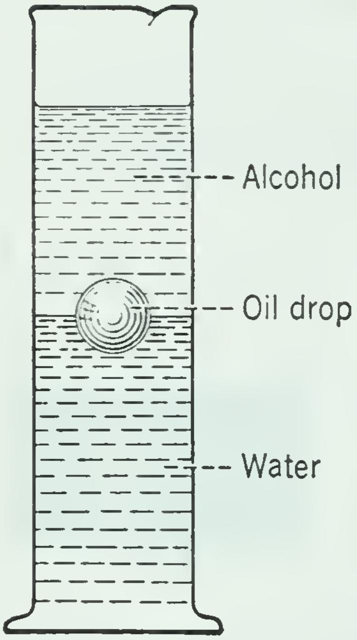


Fig. 6–19. A liquid that is free from a distorting force takes a spherical shape.

Suppose that you have a cubic inch of some plastic wax and are told to fashion it into such a shape that it will have the smallest surface area possible. By geometry, you find that a sphere has a smaller surface area for a given volume than any other geometrical figure. As the film on the surface of a free liquid contracts, it pulls the liquid into the shape of a sphere, reducing the surface area to a minimum. Mercury spilled on a table breaks up into small drops, since the effect of gravity is small compared to the cohesive force of the molecules of mercury. Larger globules are distinctly flattened.

What is capillarity? In Chapter V, the statement was made that liquids in communicating vessels seek the same level. The statement is not entirely exact, and a correction must be made for communicating tubes of small diameter. Experiment shows that water does not stand at the same level in communicating tubes of varying diameters, but rises higher in tubes of small diameter. (See Fig. 6–20*A*.) When mercury is used, the depression is greater in tubes of small diameter, Figure 6–20*B*. This elevation, or depression, of liquids in *capillary* (hairlike) tubes is known as *capillarity* and becomes apparent in tubes of inside diameters less than 2 cm.

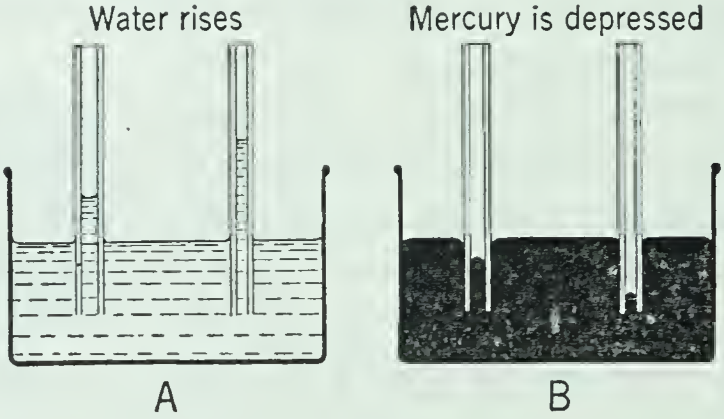


Fig. 6–20. *A*. Capillary action of water. *B*. Capillary action of mercury.

Capillarity really depends upon adhesion and surface tension. The adhesion of water for the glass causes the surface of the water to become *concave.* Surface tension tends to decrease the surface area, or to flatten it by contraction. The two forces working together lift the liquid above the surrounding level. The height to which the liquid will be lifted depends upon its weight and the strength of the liquid film. In liquids like mercury, cohesion makes the surface *convex,* and surface tension, by tending to flatten it, produces depression of the liquid in the tube.

What are the laws of capillarity? Several laws that apply to capillarity have been verified by experiment: (1) *Liquids rise in capillary tubes if they wet them; liquids that do not wet the tubes are depressed.* (2) *The elevation, or depression, is inversely proportional to the diameters of the tubes.* (3) *The amount of elevation or depression decreases as the temperature increases.*

DEMONSTRATION. What are three factors affecting capillarity? Insert glass tubes of different sizes into beakers of water, oil, mercury, and alcohol. Compare the results with the laws of capillarity. Is the elevation or depression the same for any two liquids?

Measure the height of the water in one of the capillary tubes. Heat the water and measure the height again. What effect does temperature have upon capillarity?

We meet capillary phenomena in everyday life. When one corner of a towel is held in water, other portions of the towel soon become wet. The spaces between the fibers are really small capillaries in which the liquid rises. The use of a towel in drying the hands is an application of capillarity. The absorption of ink by blotting paper and the rise of oil in a lampwick are further examples.

Capillarity may play an important part in the conservation of moisture in the soil. Rain water disappears in several ways: (1) part of it runs off directly; (2) part evaporates; (3) some trickles through the soil and becomes a part of the subterranean drainage system; (4) some of it is absorbed or held by the soil, to be used by the roots of plants. The amount thus held depends upon the kind of soil and *upon the size of its pores.* In very compact soil, the pores are small and capillary action brings the water to the surface, where it is lost by evaporation. Stirring the surface soil makes the pores larger and prevents a considerable portion of this loss. The so-called *dry farming* depends upon this principle. In Kansas, Nebraska, and other states where the rainfall is not much more than fifteen to twenty inches annually, good crops may be grown by making the subsoil compact to prevent subterranean loss, and keeping the surface stirred to prevent loss by capillarity.

By capillary action oil is drawn into the small space between a shaft and its bearing. Thus capillarity is a vital factor in the lubrication of machines.

What is the nature of solution? Everyone knows that a lump of sugar or a piece of salt put into a glass of water dissolves, or goes into solution. In these cases the water is the *solvent;* the sugar or the salt, the *solute.* It is believed that a substance dissolves if the force of adhesion between its molecules and those of the solvent is greater than the cohesive force binding together its molecules. The molecules of the solute occupy the spaces between the molecules of the solvent. It is probable that molecular motion also plays an important part in the advancement of these molecules through the pores of the solvent.

Several interesting facts concerning solutions should be noted.

(1) *A solution is of the same nature throughout;* each unit volume of the solvent contains the same amount of solute. A teaspoonful of sweetened coffee is just as sweet when taken from one part of the cup as from another.

(2) *The solute does not separate from the solvent upon standing,* unless the temperature changes or some of the solvent is lost by evaporation.

(3) *Only a definite amount of solute can be dissolved in a given amount of solvent at a certain temperature.* If the solvent holds all the solute it can at that temperature, it is said to be *saturated.*

(4) *The solubility of a solid generally increases with a rise of temperature.* Boiling water dissolves salt and sugar faster than cold

water does, and it takes more of the solute to saturate the boiling water.

(5) *The solubility of a solid varies with the nature of the solid and with the solvent used.* For example, salt dissolves readily in water, but glass is only slightly soluble. Rosin and shellac are almost insoluble in water, but they dissolve readily in alcohol. Grease is quite insoluble in water, but it dissolves readily in gasoline. On the other hand, many substances that are quite insoluble in alcohol or gasoline dissolve easily in water. Water is one of the best solvents known.

Both solids and liquids tend to lower the freezing point of a solvent when they are dissolved in it. During cold weather, men add alcohol or a glycerine solution to the water in their automobile radiators to lower its freezing point. Such substances are called antifreezes.

What is the nature of crystallization? When the saturated solution of a solid is cooled or evaporated, some of the solid separates from the solvent in the form of crystals. Crystallization may also occur when a substance changes from the liquid to the solid state. During crystallization the molecules of the solid arrange themselves in regular geometric figures. The shape of the crystal depends upon the nature of the solid and the conditions under which crystallization occurs. Granulated sugar, rock candy, and snowflakes are familiar examples of this beautiful phenomenon. The diamond differs from the graphite in your "lead" pencil only in the form in which the carbon particles of which it is composed have crystallized.

How are liquids dissolved? It is possible to dissolve one liquid in another. In such a case, either liquid may be considered the solvent. When two liquids are mutually soluble, they are said to be *miscible.* For example, alcohol and water will mix in all proportions. Oil and water are *immiscible,* that is, they will not mix. When an oily liquid is vigorously shaken with water, finely divided particles of oil remain *temporarily* suspended in the water forming an *emulsion.* Milk is a good example of an emulsion, since the fat globules remain suspended in the milk for some time before the cream separates. In making mayonnaise dressing, egg yolks are added to make the emulsion of olive oil permanent.

What is a suspension? Insoluble solids when finely divided and mixed with a liquid form what is known as a *suspension.* Muddy water is a common example of a suspension. When the suspension is very dense, such as the mud from a drillhole in boring, it is sometimes called *sludge.*

What are oil mixtures? Each kind of lubricating oil (usually they are distinguished by their S.A.E. numbers, as described on page 157) is a mixture of several compounds, all of which are mineral oils and mutually soluble. A change in the proportion of these compounds, or a dilution caused by the addition of some other liquid, changes the density and the viscosity of the oil and may make it unfit for lubricating purposes.

Dilution is caused by the gradual leakage of unburned gasoline past the piston rings into the crankcase where it dissolves in the lubricating oil. This is most common during winter driving.

Incomplete burning of oil molecules on the cylinder walls leaves particles of carbon which collect around the piston rings and increase friction. Carbon forms also on top of the pistons and the valves, where it interferes with normal heat transfer by conduction away from the cylinders, thus causing overheating. Partial burning of oil occurs, too, in the crankcase.

As you will learn in a later chapter, water is one of the products formed when such fuels as gasoline are burned. Some of the water in the cylinder of the motor, in the form of steam, leaks by the piston rings into the crankcase, and there it condenses. The churning of water and oil in the crankcase forms an emulsion, and, also, a suspension of particles of carbon, dust, and dirt. This combination of emulsion and suspension makes a black creamy substance; it is a kind of sludge.

Demonstrations. 1. Dissolved substances have what effect upon the density of water? Into each of five hydrometer jars or graduates pour the following: pure water, denatured alcohol, a 50% solution of alcohol in water, a 75% solution of alcohol in water, and a solution of table salt. Test each of the five liquids with a hydrometer. (See Fig.

2–14.) Compare the densities. Increased concentration of alcohol in water has what effect upon density? How does the density of salt solution compare with that of pure water?

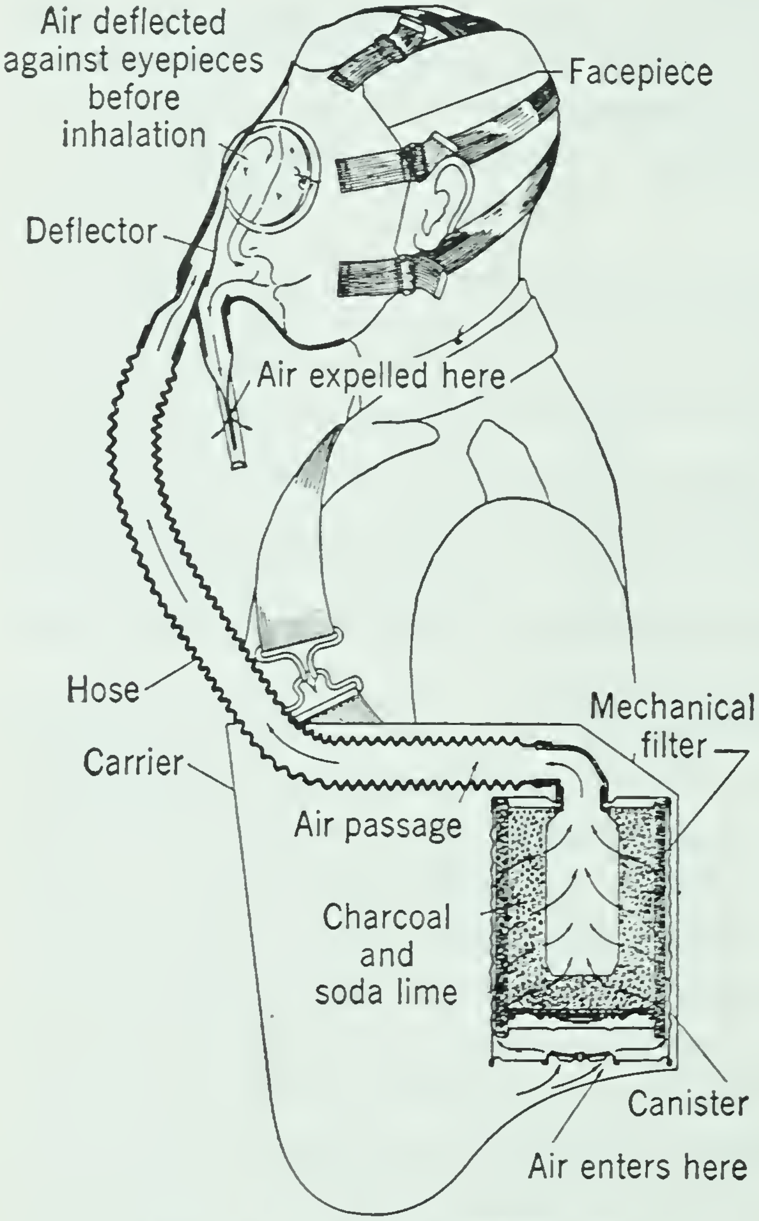
2. To a test tube half full of water add a few drops of oil and shake it. Do the liquids mix? Add a few drops of liquid soap and shake it again. Explain the difference between these two tests.

3. Obtain a sample of sludge from a filling station and examine it.

3. ADSORPTION AND ABSORPTION OF GASES

Sometimes the adhesive force between the molecules of a solid and the molecules of a gas is so great that the gas molecules are attracted to the surface of the solid where they are held crowded closely together. This effect upon the surface of a solid is called *adsorption.* Be sure not to confuse this term with *absorption,* which means a mixing of molecules in solution. Solids *adsorb* molecules and liquids *absorb* molecules.

How are gases adsorbed by solids? Some porous solids, like charcoal and meerschaum, have a great capacity for adsorbing gases. Freshly heated charcoal adsorbs 90 times its own volume of ammonia gas; it will adsorb 35 times its volume of carbon dioxide. The adsorption of gases by solids appears to be due to a condensation of the gas upon the surfaces of the solid; hence porous solids, having large surface areas, naturally have a great capacity for adsorption. Tailors put fuller's earth on a grease spot and then add gasoline. The gasoline dissolves the grease which is adsorbed by the fuller's earth as fast as it dissolves. Charcoal is a good deodorizing agent, since it readily adsorbs the gases that give rise to the odors. It was used extensively in World War I for filling gas masks. It is very efficient in adsorbing poison gases, especially when it is impregnated with certain chemicals. Children in the United States collected coconut shells, pits, and nuts to be used for making charcoal for gas masks. It was learned that charcoal made from these substances is about nine times as adsorptive as that made from ordinary soft woods. (See Fig. 6–21.) The gases that are given off by such foods as fish and onions are readily adsorbed by butter. For this reason butter kept in a refrigerator with onions soon acquires an "onion taste." A perforated can filled with charcoal may be used in a refrigerator to prevent the adsorption of gases by foods. Silica gel is useful too.



Army gas mask showing passage of inspired and expired air

Courtesy of the War Department

FIG. 6–21. This official gas mask contains activated charcoal for adsorbing gases. The charcoal is impregnated with various chemicals which unite with the poison gases and form harmless compounds.

How are gases absorbed by liquids? Milk absorbs gases given off by foods quite as readily as does butter. If we heat a little water in a test tube, bubbles of gas soon begin to rise through the water. This gas may be shown to consist of air which was absorbed by the water. Water absorbs carbon dioxide even more readily than it does air, while ammonia gas is so readily absorbed that it is possible to dissolve nearly 1300 quarts of ammonia gas in one quart of ice water.

Heating a liquid decreases its capacity for absorbing gases. In other words, gases are *less soluble* in hot water than they are in cold water. For this reason ammonia gas is liberated when we heat household ammonia.

An increase of pressure increases the capacity of liquids for absorbing gases. In charging soda fountains, or in bottling carbonated beverages, carbon dioxide gas is forced into the liquid under a pressure of several atmospheres. When the pressure is released, part of the absorbed gas bubbles off and escapes at the surface of the liquid. The effect of pressure upon gas absorption was studied quantitatively by Henry. He found that *the amount of gas that can be absorbed, or dissolved, in a liquid is directly proportional to the pressure.* This statement is known as HENRY'S LAW. At a pressure of two atmospheres, you can dissolve twice the amount of carbon dioxide in water, for example, that you can when the pressure is only one atmosphere.

In many cases gases which are dissolved in water are held in solution physically. In other cases, the gas unites with the water to form a chemical compound which is soluble; in either case the result is a mixture of molecules and the process is called absorption.

Gases expand. If we put a pint of milk in a quart bottle, the milk does not expand and fill the entire bottle. If we puncture an inflated tire, the air that was inside the tire expands as it escapes and occupies much more space than it did formerly. We can easily measure the volume of a liquid, such as milk or water, but the volume or space that a gas occupies depends upon the pressure to which it is subjected. Suppose we blow up a rubber balloon until it is about half inflated. Next let us put it under a bell jar and exhaust the air that surrounds the balloon. As we remove the air from the bell jar, we are reducing the pressure on the outside of the balloon. The gas inside expands and increases the volume of the balloon decidedly. If we let the air back into the bell jar, the balloon will shrink to its former size. This experiment shows that gases are perfectly elastic. (See Fig. 6–22.)

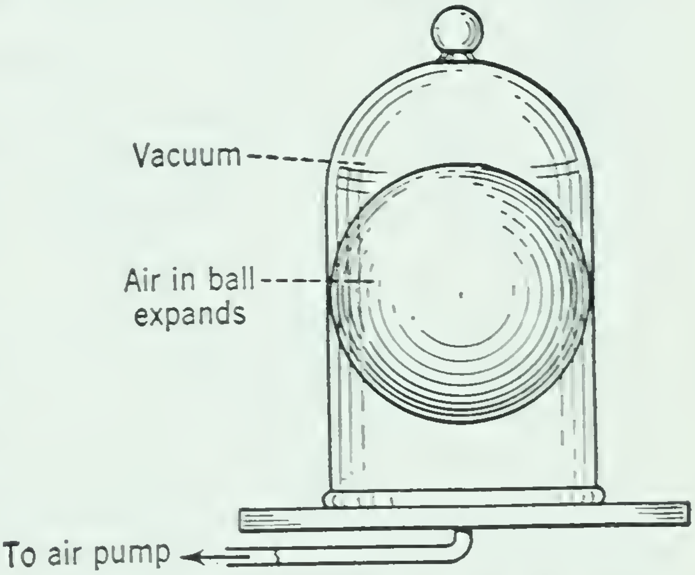


FIG. 6–22. Gases expand when the pressure upon them is decreased.

Demonstration. Place a partly inflated toy balloon under a bell jar and exhaust the air. Note any change in size of the balloon. Explain. Allow the air to re-enter the bell jar. Note any change in size of the balloon and explain.

What are standard temperature and pressure? If a carpenter wishes to cut a board 12 ft. long, he does not bother to read the thermometer or the barometer. In selling gasoline, the attendant does not read the thermometer as he measures out each gallon. It is true that the dimensions of both solids and liquids do vary to some extent with the temperature and the pressure applied to them, but the variation is so small that it is usually neglected. For very great accuracy, both temperature and pressure corrections become necessary in the measurement of solids and liquids. For example, the *standard meter is exactly one meter long only when the temperature is 0° C.*

Because gas volumes vary so much, it is always necessary to consider both the temperature and the atmospheric pressure when we wish to measure them. To prevent confusion, physicists have agreed upon *0° C. as the standard temperature* to be used. They have also agreed upon the pressure of a column of mercury *760 mm. high, or 76 cm., as the standard pressure.* This represents average atmospheric pressure at sea level. The abbreviation S.T.P. is used to indicate *standard temperature and pressure.* For example, if we speak of a gas as having a volume of 1000 cc., we mean that that is the volume which the gas occupies when its temperature is 0° C., and the pressure applied to it is equal to one atmosphere, or 76 cm. of mercury. At a different temperature and pressure, its volume will be decidedly different.

Liquids are not easy to compress. It is so hard to compress liquids that we consider them almost incompressible. Water, for example, is so nearly incompressible that it takes the stupendous pressure of 20 tons to reduce the volume of 1 cu. in. by only 0.1. This means that the water at the bottom of the ocean is only slightly more dense than it is near the surface.

We learned, however, that gases are easily compressed, and that the air at sea level is about twice as dense as it is at the top of

Mt. Blanc. The air at sea level is compressed by the weight of the upper layers of air that it sustains.

What is Boyle's law? Robert Boyle was the first person to perform experiments upon what he called the "springiness of the air." No doubt others had known something of compressed air, but no one had taken the trouble to find out how the volume of a gas is really affected by the pressure which it sustains.

Boyle used a J-shaped tube for his study. He added enough mercury to fill the bent portion of the tube and adjusted the levels so that the mercury would stand at the same height in both arms of the tube. Then he had a volume *V* of air confined in the short arm of the tube. Next he measured the length of the tube so that he could determine the volume of gas confined. He knew that this gas must be under the same pressure as the air, because the mercury levels were equal. (See Fig. 6–23*A*.)

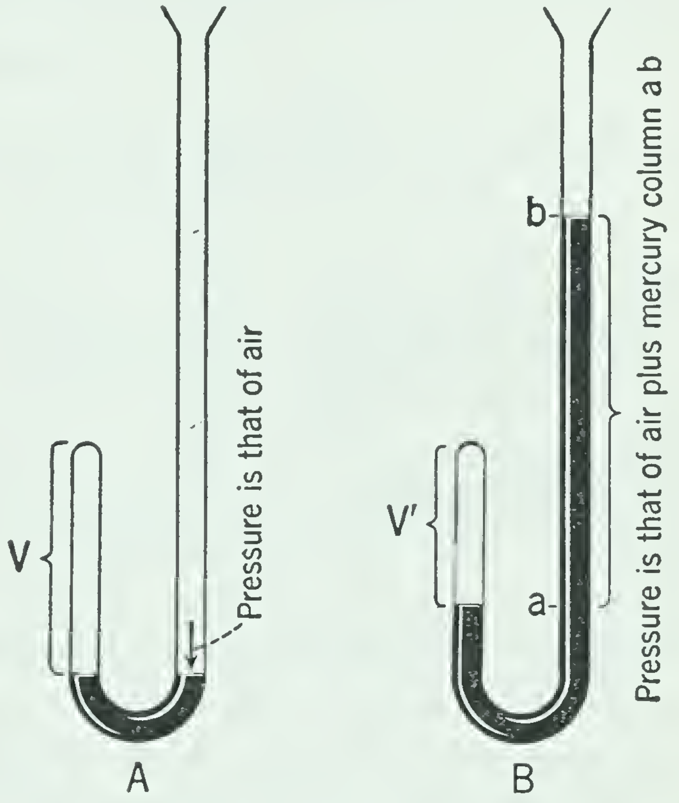


Fig. 6–23. Apparatus used to demonstrate Boyle's law.

(1) By reading the barometer, he could find the exact pressure to which the enclosed volume of air was subjected. Let us call that pressure *P*. Next he added more mercury to the long arm of the tube, as shown in Figure 6–23*B*.

(2) By measuring the length of the column of air enclosed, he could determine the new volume *V′*. He could find the new pressure *P′* by measuring the length of the mercury column *ab* and adding that length to the barometer reading.

As a result of several trials with such an apparatus, Boyle found that increasing the pressure upon a volume of confined gas reduced its volume correspondingly. Doubling the pressure reduced the volume to one-half; trebling the pressure reduced the volume to one-third. BOYLE'S LAW may be stated as follows: *The volume of any dry gas, the temperature remaining constant, varies inversely with the pressure sustained by it.* Since one factor increases as the other decreases, *the product of the volume and its corresponding pressure is always a constant quantity.* Stated algebraically:

$$VP = \text{a constant}$$

In all cases, except under *very high* pressures:

$$VP = V'P'$$

V' represents the *new* volume, and P' the *new* pressure.

Boyle's law applied to gas engines. Application of Boyle's law can be seen in the cylinder of an internal-combustion engine. (Fig. 14–6). As the piston moves downward on the intake stroke the air space inside the cylinder increases, thus reducing the air pressure. The space above the piston is then a partial vacuum. We may restate Boyle's law to fit its application in the cylinder as follows: *If temperature remains constant the pressure which a given weight of gas exerts varies inversely with its volume.* As the piston continues downward the inlet or intake valve opens, allowing a mixture of gas and air to be forced in by outside air pressure. On the next stroke, called the *compression stroke,* all valves being closed, the volume of the gas mixture above the piston is decreased, thus increasing the pressure. This increased pressure, which ranges from six to seven times normal air pressure, increases the density of the gaseous fuel mixture. The greater the weight of mixture per unit volume the greater the force in the power stroke. The operation of the gas engine will be discussed in a later section.

Boyle's law applied to the exhaust pump. A pump used to exhaust air from vessels and produce a partial vacuum was invented by Otto von Guericke in 1650. For such a pump, there must be a cylinder, a piston, and valves. The piston fits the cylinder so tightly that air cannot pass, and a rod is attached to it so that the piston can be moved up and down, or to and fro, from one end of the cylinder to the other. A valve acts like a policeman at the exit of a one-way street. He permits traffic to move in one direction *only.* The valve opens to permit air to flow in one direction, but closes so that it cannot flow the other way.

While the piston represented in Figure 6–24 is pulled up the cylinder, the valve V_2 remains closed. The air that was above the piston is pushed out through a small hole in the top of the cylinder. A *partial vacuum* is produced below the piston as it rises. The air in the bell jar expands, and part of it flows through the valve V_1 into the partial vacuum in the lower end of the cylinder. When the piston is lowered again, the valve V_1 closes so that the air cannot flow back into the bell jar. The air then forces its way up through the valve V_2 of the descending piston. On the next upstroke of the piston, the operation is repeated. The air above the piston is pushed out, and more air flows over into the lower end of the cylinder from the bell jar. Each upstroke of the piston removes part of the air from the vessel that is to be exhausted.

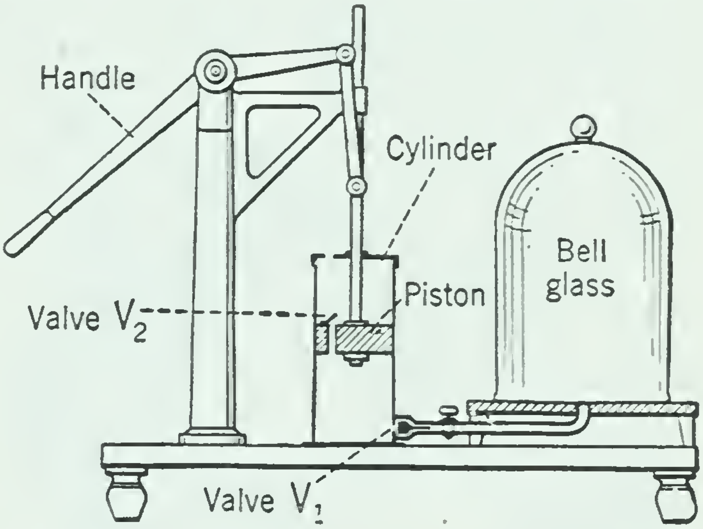


FIG. 6–24. Such a pump is used for pumping air or other gases. It is a vacuum pump.

Supposing the cylinder and the bell jar to be both of the same size, one-half the air will flow into the cylinder during the upward stroke of the piston, and one-half of the air will be removed at the completion of one stroke of the pump. During the next complete stroke, one-half of the remaining air or one-fourth of the original amount is removed. The next stroke removes one-half of what remains, or one-eighth of the original amount. The action continues thus until the expansive force of the air finally becomes too weak to operate the valves of the pump.

What are some uses of the exhaust pump? Some type of exhaust pump is used whenever it is necessary to remove a part or all of the air from a container. Unless the air is removed from an electric-light bulb, the filament will burn. In some types, the bulb is then refilled with a gas which has no effect upon the filament. In making X-ray bulbs, radio tubes, and thermos bottles, an exhaust pump is used. Milking machines use a vacuum pump.

Liquids boil at a lower temperature in a vacuum than under air pressure, and they evaporate much more rapidly in a vacuum. The principle of vacuum drying is used when dyestuffs and chemical crystals are dried in *vacuum pans.* Some of our *dried* or *dehydrated* foods have had much of the water they contained removed by being dried in a vacuum pan.

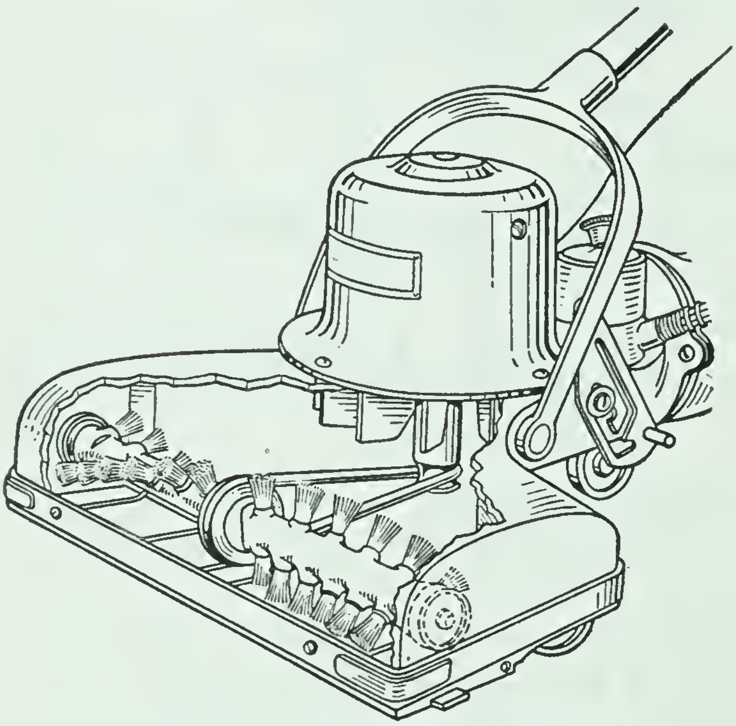


Fig. 6–25. The revolving brush beats the rug gently, and the dirt is pushed into the partial vacuum produced by an electric motor.

In sugar refineries, vacuum pans are used during the evaporation of the sugar solution, since evaporation occurs more rapidly and a lower temperature may be used to avoid the danger of scorching the crystals.

The *vacuum cleaner* also furnishes a practical application of the exhaust pump or exhaust fan. In the latter case, a fan is driven by an electric motor. The fan pushes the air away in front of the blades, and leaves a partial vacuum on the other side of the fan. As the air rushes in through the mouthpiece of the tube leading to the fan chamber, it carries with it the dust particles from the article that is being cleaned. A rotary brush is sometimes used to sweep and beat the rug or carpet at the same time in order to loosen the dirt. (See Fig. 6–25.)

Boyle's law applied to the compression pump. The bicycle-tire pump, or automobile-tire pump, furnishes a common example of compression pump. Such pumps are used to push or crowd more air into a container. In one of the simple types, shown in Figure 6–26, a leather disc attached to the piston permits the air to flow past it in one direction, but not in the other. Hence it takes the place of a valve in the piston. The other valve may be placed in the outlet tube; with pneumatic tires a valve is placed in the valve stem of the tire itself.

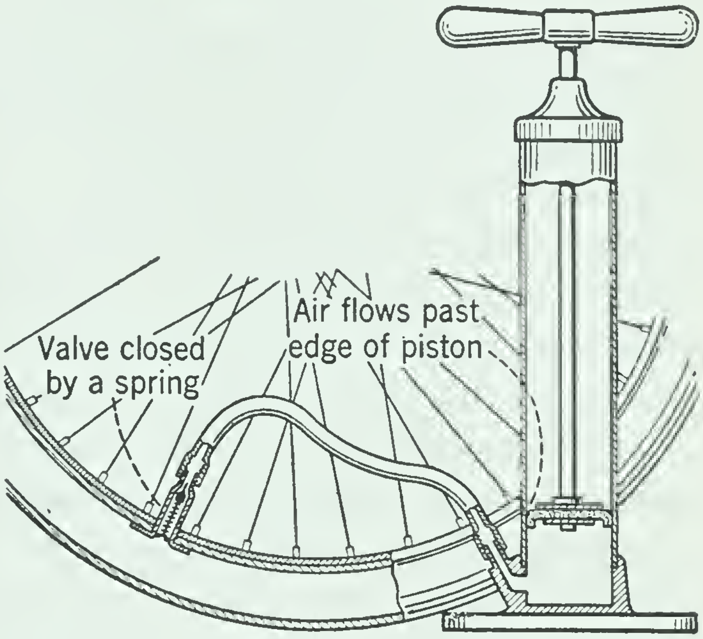


FIG. 6–26. A simple compression pump used to inflate a pneumatic tire.

Figure 6–27 shows the construction of one type of compression pump. The piston has no valves, and fits the cylinder so tightly that air cannot pass. The valves are so arranged that air enters through one as it leaves through the other. On the upstroke of the piston the air above it is pushed out of the cylinder. Valve V_1 opens to permit air to enter through A. On the downstroke this valve closes and valve V_2 opens as the piston pushes the air out of the lower part of the cylinder.

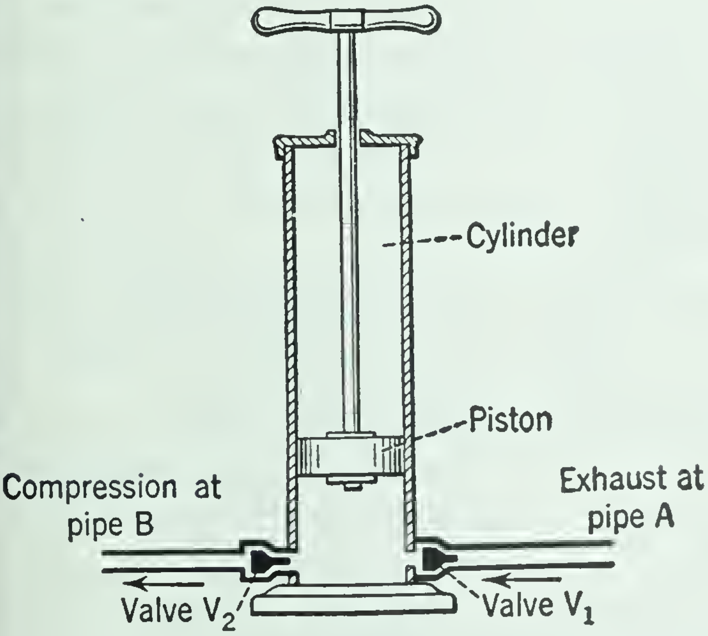


FIG. 6–27. This compression pump may also be used as an exhaust pump.

Such a pump may be used as either an exhaust or a compression pump. If a vessel is attached at A, it will be exhausted as the pump operates, while air is being compressed in a vessel attached at B. Thus, a reversal of the direction in which the valves open may convert a compression pump into an exhaust pump, or vice versa.

What uses are there for compressed air? For two reasons there are many uses for compressed air: (1) When air is put under a pressure of several atmospheres, it is capable of exerting great expansive force. (2) It is particularly satisfactory, since strong-walled tubes can be used to transmit this force to considerable distances. We use compressed air to drive our machines, to stop our railroad trains, to carry mail, and to fill our tires.

(1) *Pneumatic tires.* The compressed air in our automobile tires forms an elastic cushion to absorb the shocks which we encounter on rough roads. As we pump up a pneumatic tire, we are applying Pascal's law to gases. The pressure applied to the valve stem is transmitted undiminished to every unit area of the inside of the tire.

(2) *The Westinghouse air brake.* The flanged wheel, invented by Stevens, and the air brake, invented by Westinghouse, have made it possible to run trains at high speeds. After Westinghouse conceived the idea of a set of brakes which could be applied by the engineer to every car in the train at the same time, he was at a loss to find a satisfactory fluid to operate the brakes. The story is told that a young lady called at his office to sell him a magazine. At first he refused to buy, but reconsidered when he took a moment to look at the young lady. In that magazine he found an article describing the use of compressed air for operating some of the tools used for tunnel-construction work in Europe. He decided then to try compressed air for operating his newly invented brakes.

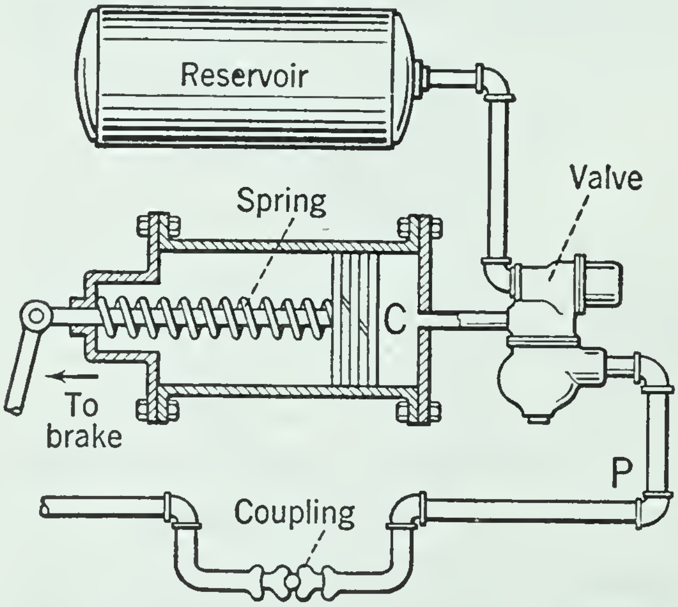


Fig. 6–28. The Westinghouse air brake.

The air brake may be operated directly from the engine or it may operate automatically from an auxiliary reservoir of compressed air stored under the car itself. In Figure 6–28 *P* is a pipe connected with the main reservoir on the engine, in which a compressor maintains a pressure of about five atmospheres. The reservoir communicates with *P* through a triple valve. This valve maintains communication between *P* and the reservoir and shuts out the air from *C*, as long as the pressure from the engine is supplied to *P*. When this pressure is diminished, either intentionally by the engineer or accidentally by the breaking of the coupling, the valve opens in such a way that air from the reservoir flows into *C* and forces the brake piston to the left, thus setting the brakeshoes against the wheels. Readmission of air through *P* lets the air in *C* escape and the spring releases the brakes.

(3) *Diving bells and diving suits.* If we force a tumbler under water, mouth downward, the pressure of the water compresses the air in the tumbler to some extent, the amount of compression depending upon the depth. The air in a *diving bell* is compressed in a similar manner as it is lowered in the water. (See Fig. 6–29.) In the modern diving bell the workmen are supplied with air forced down through a tube connected with a compressor at the surface. The air is supplied fast enough to force all the water out of the bell and keep a stream of bubbles flowing out from its lower edges. (See Fig. 6–30.)

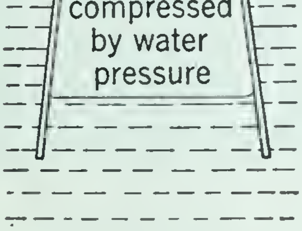


FIG. 6–29. Diving bell being lowered into the water.

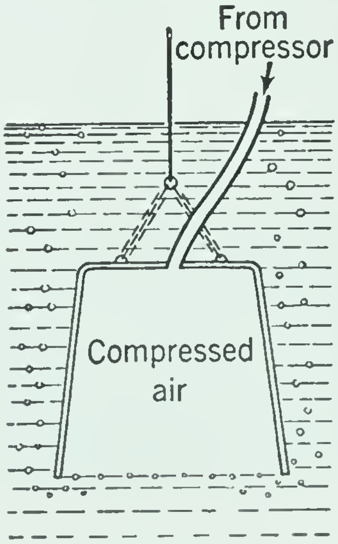


FIG. 6–30. Diving bell being supplied with compressed air.

The *diving suit* is sometimes supplied with compressed air in the same manner as the diving bell. In other cases the diver has a self-contained apparatus and is independent of a compressed-air supply line. He carries a tank of compressed air. By opening a valve he permits air to escape just fast enough to keep his suit filled with air. A constant stream of bubbles passes out through a valve in his suit.

(4) The *pneumatic caisson* is used for constructing bridge piers or foundations under water. The caisson is open at the lower end and it is weighted so that it will sink, not only in water, but also into the mud at the bottom. (See Fig. 6–31.) Compressed air is used to keep the water out of the caisson. The workmen enter the caisson through air locks, or combinations of airtight doors, and material is passed down to them in the same manner. Thus the foundation may be built inside the caisson. For tunnel construction jacks are used to push forward a cylindrical shield as the material is removed by workmen. The tunnel lining is constructed inside the shield.

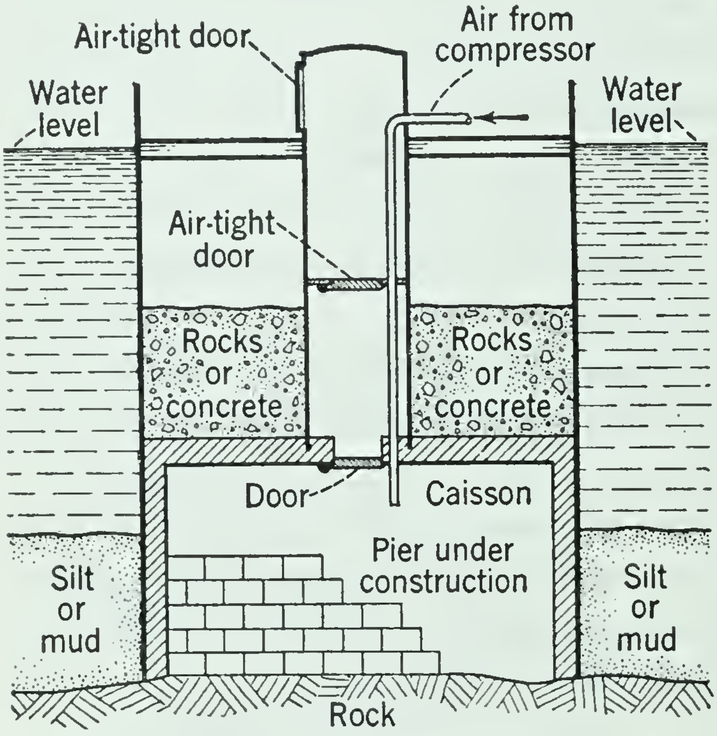


FIG. 6–31. Sectional view of a pneumatic caisson.

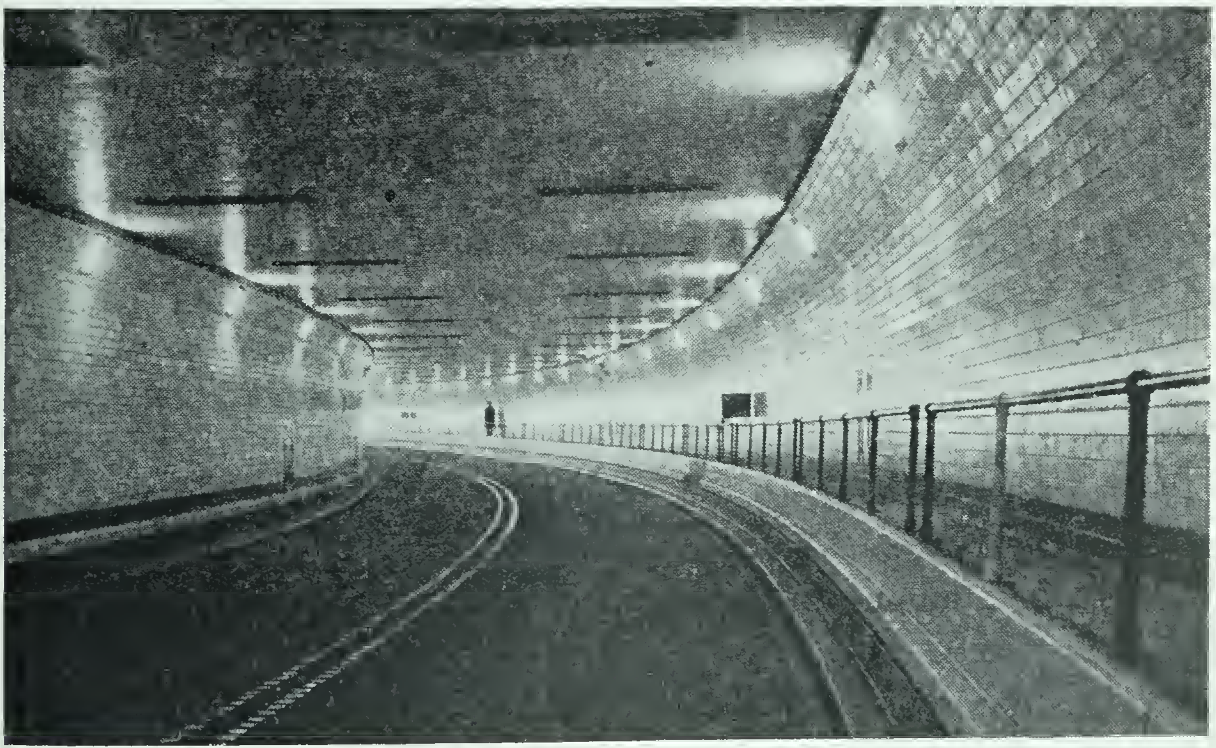
(5) *Pneumatic despatch.* In some large buildings compressed air is used for transmitting cash boxes and small packages. It has also been used for transmitting mail between the post office and the railroad stations, although the system has generally been replaced by the motor truck. The cylindrical carrier, which is slightly smaller than the tube, has packing rings near the ends to make it fit the tube fairly tightly without much friction. An exhaust pump at the receiving end and a compression pump at the

transmitting end of the tube produce a difference of pressure that is sufficient to drive the carrier through the tube with considerable speed.

(6) *Other uses for compressed air.* Many tools are operated by compressed air. These include *riveting hammers, rock drills, the sandblast for cutting and polishing,* and *some rotary tools.* The *bellows* are used to produce a forced draft for making a blacksmith's forge hotter, or to supply compressed air for organ pipes or for starting fires. They are indirectly used to produce the partial vacuum needed for the operation of player pianos.

Mines and large buildings are often ventilated by compressed air. It is used to operate car doors and for various regulating devices. In submarines it is used to force the water from the various chambers, and it operates the propellers which drive torpedoes.

Compressed air ventilates the tunnels beneath the Hudson River. Several years ago the Holland Tunnel was built for vehicular traffic under the Hudson River from New Jersey to the city of New York. Recently the Lincoln Tunnel was opened. (See Fig. 6–32.) The



Courtesy of the Port of New York Authority

FIG. 6–32. Inside view of the Lincoln Tunnel which was built to carry vehicular traffic under the Hudson River.

Holland Tunnel consists of two tunnels, each 29 ft. 6 in. in diameter, laid side by side beneath the Hudson River. More than a mile, 5,480 ft., of the length of these tunnels is beneath the river. This tunnel is designed to have a capacity of 2000 automobiles per hour. More than a million cars have passed through the tunnels since they were opened.

The problem of ventilating these tunnels was quite as difficult as that of constructing them. Two ventilating buildings at either end were constructed to supply compressed air to remove the dangerous carbon monoxide which comes from the exhaust of all automobiles. In each building there are 21 large electric fans, some of them used to compress air, which then enters the tunnel near the bottom; and some of them for exhausting the air from the ducts at the top. Although these compressors can force 1,900,000 cu. ft. of air into the tunnels per minute, there is no longitudinal draft in the tunnel. The air rises to the exhaust ducts directly. (See Fig. 6–33.) Traffic moves rapidly through tunnels, and the ventilation seems to be adequate.

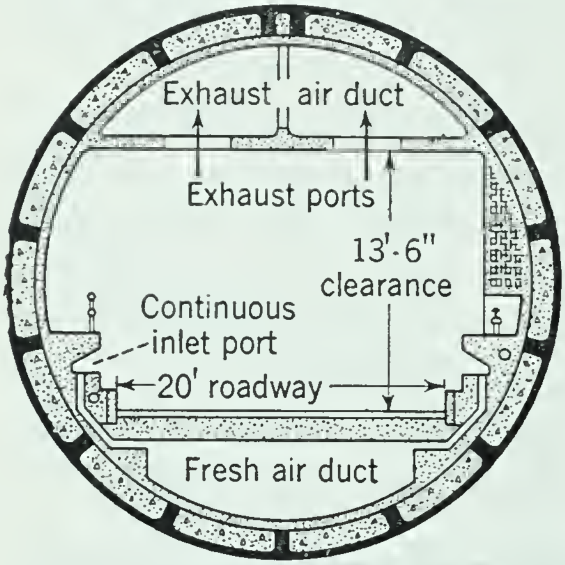


Fig. 6–33. Cross-sectional view of one of the tunnels under the Hudson River. The diagram shows how tunnel is constructed.

Bernoulli's principle. In the eighteenth century Daniel Bernoulli stated this law: *If the speed of a liquid passing through a tube increases at any point, the pressure of the liquid decreases at that point.* Look at Fig. 6–34. When water flows through the tube in that drawing, its velocity is increased as it flows through the pinched or constricted section of the

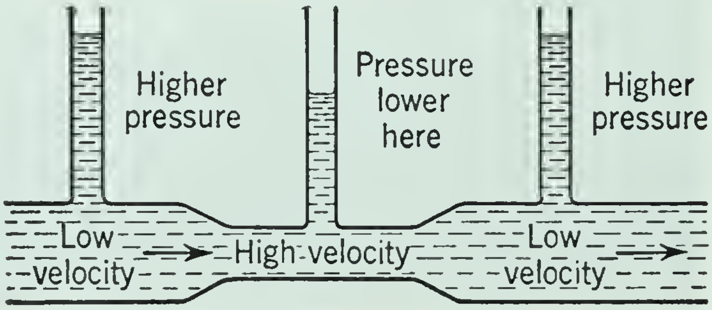


Fig. 6–34. As the water flows more rapidly through the constriction in the tube, the pressure is lowered.

tube. A tube having this kind of constriction is called a *Venturi tube.*

By noting the water levels in the pressure tubes extending vertically from the Venturi tube, Figure 6–34, you can see that the pressure has decreased as the velocity of the water has increased. It is possible to calculate, from the difference in pressure in the vertical tubes, the velocity of the water in the horizontal tube. A meter which makes use of this principle is called a *Venturi meter.*

It has been found that Bernoulli's principle applies to gases as well as to liquids. Venturi tubes have been used, for example, on the wings of airplanes to determine air speed. And you will see, a few pages later, other applications of Bernoulli's law to the flight of airplanes. (See pages 181–182.)

Application of Bernoulli's principle to the baseball and the tennis ball. A baseball which is not spinning may travel in a straight line. But any boy knows that a spinning ball will move along a curved path. If we refer to Figure 6–35, we find that the explanation is quite simple. The ball, spinning in a counterclockwise direction, drags the adjacent air around with it, as represented by the dotted circles. At the top of the ball this air is *moving with* the air current set up by the forward motion of the ball, and at the bottom it is *moving against* these currents. The air at the top moves faster and the pressure there is reduced. Thus the ball will move along the path shown by the dotted curve.

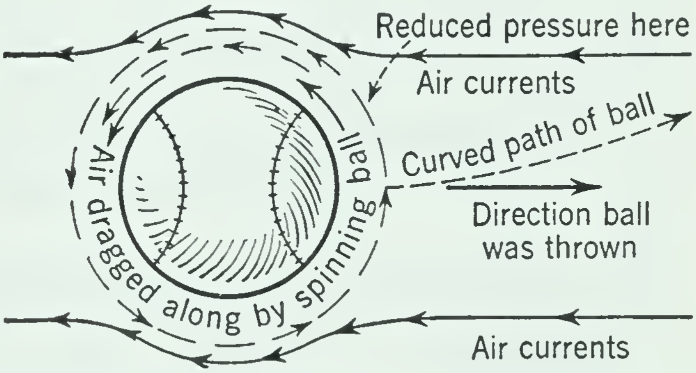


Fig. 6–35. The curving baseball is an application of the Bernoulli principle.

When a tennis player hits the ball a glancing blow, he imparts to it a spinning motion. Then it travels along a curved path, and it takes a peculiar bound. A "sliced" or "hooked" golf ball is also an application of Bernoulli's principle.

What is the aspirator? A suction pump, or aspirator, is often

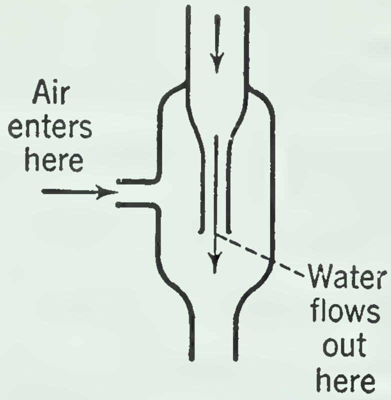


Fig. 6–36. A vacuum can be produced by an aspirator. Water drags along with it the air molecules.

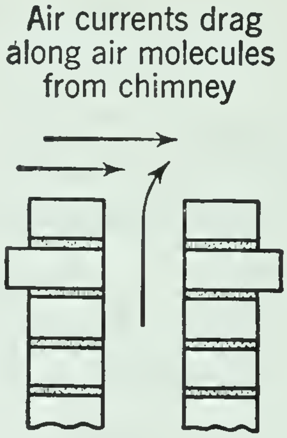


Fig. 6–37. Wind blowing over top of chimney produces a partial vacuum.

used in the laboratory to produce a partial vacuum. It is screwed to a water faucet, and the vessel to be evacuated is attached to the tube on the side of the pump. (See Fig. 6–36.) As a current of water flows rapidly through the inner tube, it drags along with it air molecules from the vessel to be exhausted. The air in the vessel expands and more molecules are carried away by the running water. In this manner, quite a good vacuum can be produced in a short time.

The atomizer uses the ejector principle. When the wind blows across the top of a chimney, the rapidly moving current of air carries along with it some of the gas molecules within the chimney. (See Fig. 6–37.) The gases within the chimney expand, and their density is decreased. For this reason a chimney draws much better on a windy day.

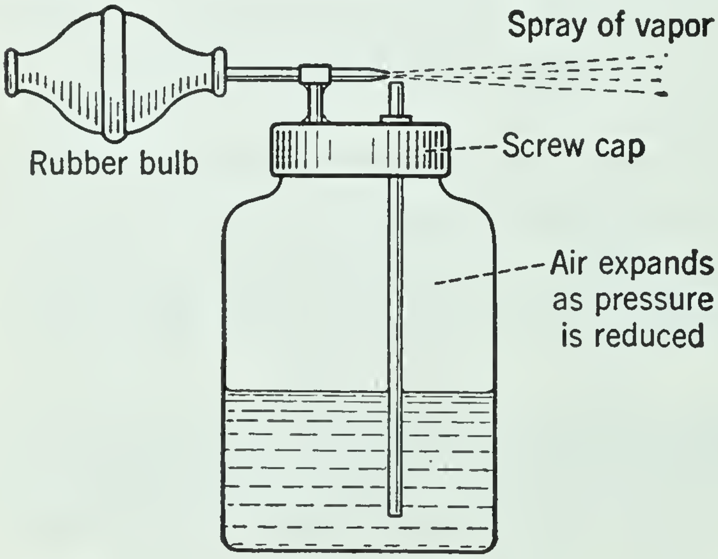


Fig. 6–38. The atomizer as used to form a spray.

The *atomizer* is an application of the *ejector* principle. A small tube extends down through the stopper into the liquid in the bottle, as in Figure 6–38. Fastened to the stopper is a tube set at right angles to and just on a level with the end of the vertical tube. When the bulb, which is attached to the horizontal tube, is squeezed, a stream of air is forced across the top of the tube, thus reducing the air pressure inside, just as the wind blowing across the top of a chimney reduces the air pressure inside. The air inside the bottle then expands and pushes the liquid out through the tube, where it is broken up into spray by the blast of air from the bulb.

Demonstration. Construct an atomizer by using a glass bottle, partly filled with water, and two glass tubes. Insert one glass tube into the bottle and blow across its open end with the other tube. Explain why the water rises in the first tube.

How is an airplane supported? Since airplanes are heavier than air, they must be partially supported by the *upward* component of some force. The wing, or airfoil, has its front edge slightly higher than the rear edge. (See Fig. 6–39.) In normal flight, the angle amounts to only a few degrees, varying from 3 to 6. As the airplane is pulled or pushed forward by the propellers, a breeze is produced which makes the same conditions as if a strong wind were blowing against the airplane and the airplane were standing still. In Figure 6–39 the arrows show the direction of the wind against the plane. Thus the wind exerts a pressure, CS, acting nearly at right angles to the plane. This wind force is resolved into two components, one acting vertically, and represented by CF; the other component, CD, opposes the action of the propeller. This upward component is called the *lift*, and the

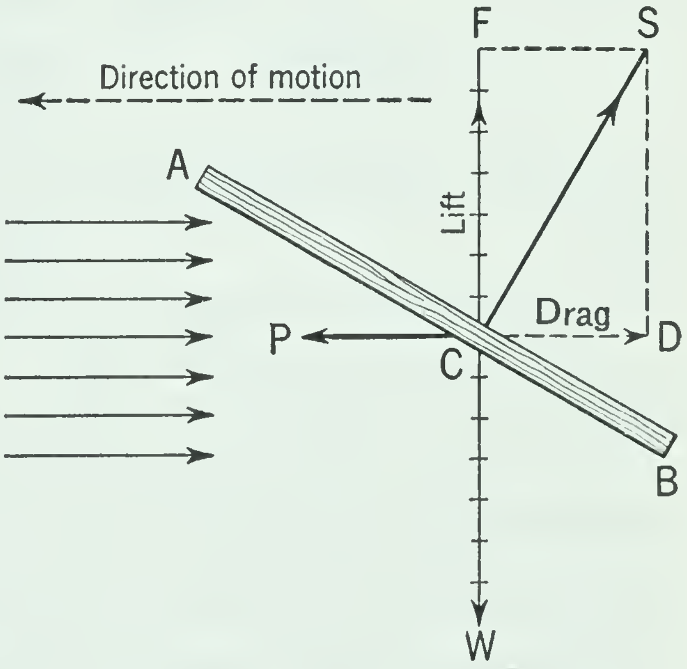


Fig. 6–39. The wind force is resolved into one upward and one horizontal component.

other component the *drag.* To keep the airplane in steady flight, the *lift* force must equal the weight of the plane, and the *drag* force must balance the forward drive of the propellers.

There is another factor which plays an important part in supporting an airplane. As the plane moves forward, the air slides along the surfaces of the plane. But it moves much more rapidly over the upper surface of the plane. Just as the wind blowing across the top of a chimney drags air molecules along with it and reduces the pressure of the air in the chimney, so the rapidly moving air reduces the air pressure *above* the plane. Since the air pressure against the lower surface of the plane is greater than that above, the difference in these pressures helps support the plane. This is really an application of Bernoulli's principle, which, as applied to the airplane wing, might be restated as follows: *the high velocity of the air moving past the upper surface produces low pressure against that surface.* (See Fig. 6–40.)

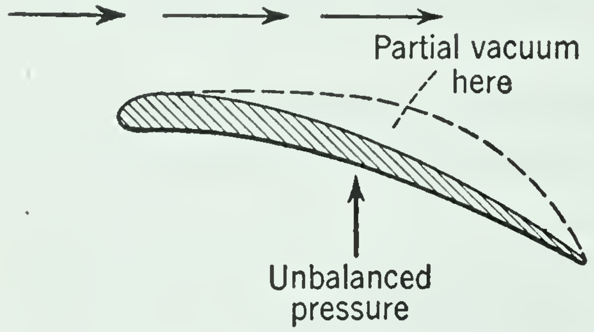


FIG. 6–40. The unbalanced pressure helps to support the airfoil, or plane.

The slight angle at which the airplane wing is set causes it to act as a variety of Venturi tube. As air flows over the upper surface of the airfoil (the wing), its velocity increases and its pressure drops. So, an area of low pressure is formed. But on the undersurface of the airfoil there is an area of great atmospheric pressure. The wing tries to move away from the area of high pressure up into the area of low pressure. Thus lift is produced.

The Venturi tube is used in carburetors. When the piston of a gasoline engine moves downward on the intake stroke (see Fig. 14–6) a partial vacuum is produced within the cylinder. The resulting unbalanced pressure between the cylinder and the outside air causes air to try to get in to fill that partial vacuum. Since the only entrance to the cylinder is through the carburetor, the air rushes into the Venturi tube (see Fig. 14–19). The constriction in the tube increases the air's velocity and at the same time lowers the pressure at the carburetor nozzle. The pressure on the fuel is of course atmospheric pressure, and lowering the pressure at the nozzle allows atmospheric pressure to force the fuel to the nozzle and out into the passing air stream and then into the cylinder. While in the air stream the liquid fuel is atomized, vaporized, and mixed with air in preparation for combustion. We shall study combustion in a later chapter.

Demonstration. Find an old carburetor and take it apart. Locate the Venturi tube and nozzle. Illustrate, if you can, how the atomizer principle speeds up the rate of the vaporization of gasoline.

SUMMARY

1. All matter is made up of exceedingly small particles called molecules. These molecules are always in motion.

2. There are several evidences of the correctness of the kinetic theory of matter. For example, gases expand indefinitely; the movement of particles in a solution can be detected with the ultramicroscope; gases exert pressure upon the walls of their containers; gases diffuse rapidly; gases pass through membranes by osmosis.

3. The diffusion, evaporation, and osmosis of liquids are all evidences that their molecules are in motion. The diffusion and evaporation of solids furnish evidence of molecular motion.

4. Cohesion is the force of attraction between like molecules; adhesion is the force of attraction between unlike molecules.

5. When an object rebounds, the angle of rebound is equal to the angle of incidence, provided that the object is perfectly elastic.

6. Hooke found that elastic deformations are directly proportional to the distorting force, if the elastic limit is not exceeded. Or, strain is directly proportional to stress.

7. Liquids behave as if a thin elastic film were stretched over their surfaces. The film is contractile. It pulls free liquids into a spherical shape.

8. The elevation or depression of liquids in tubes of small diameter is known as capillarity. Liquids that wet the tubes are elevated by capillary action; those that do not wet the tubes are

depressed; the amount in either case is inversely proportional to the diameter of the tube. The amount is also inversely proportional to the temperature.

9. The solubility of a solid usually increases as the temperature increases. Cooling a saturated solution, or evaporating some of the solvent, causes the separation of some of the solute in the form of crystals.

10. The solubility of gases decreases with an increase in temperature.

11. The amount of gas that can be dissolved in a liquid is directly proportional to the pressure, a statement known as Henry's law.

12. Unlike liquids, gases placed in a container expand and fill the container. Gases also differ from liquids in that they are easily compressed.

13. Robert Boyle found that at constant temperature a given volume of dry gas varies inversely as the pressure sustained by it. The density of a gas increases with increased pressure.

14. Compressed air is used in pneumatic tires, diving bells, air brakes, riveters, and drills.

15. Exhaust pumps are used in making thermos bottles, electric-light bulbs, radio tubes, X-ray tubes, and in ventilating systems. Some types of water pumps and the siphon depend upon the pressure of the air for their operation.

16. Bernoulli's principle states that if the speed of a liquid or gas increases at any point there is a resulting decrease in pressure at that point.

17. Applications of Bernoulli's principle are found in the curve of a ball, the aspirator and the atomizer, the lift of airplanes, and the carburetor.

How many of the following terms can you define or explain?

Cohesion
Adhesion
Kinetic theory of matter
Ultramicroscope
Diffusion
Osmosis
Safety factor
Surface films
Viscosity
Capillarity
Solution
Emulsion

Evaporation
Strain
Stress
Elasticity

Antifreeze
Boyle's law
Bernoulli's principle
Venturi tube

SELF-TESTING EXERCISES

ANSWER THESE QUESTIONS

On a separate sheet of paper numbered from 1 to 7 write the letters for the phrases that answer the following questions correctly.

1. Which of the following terms correctly describes the process of intermingling of gases without regard to weight? (*a*) Osmosis; (*b*) solution; (*c*) diffusion; (*d*) evaporation.
2. Which of the following statements is correct? The fact that liquids evaporate is evidence that (*a*) liquids are elastic; (*b*) molecules are in motion; (*c*) the boiling point is high; (*d*) the liquid is viscous.
3. Which of the following terms correctly describes the diffusion of gases or liquids through a plant or animal membrane? (*a*) Adhesion; (*b*) cohesion; (*c*) osmosis; (*d*) capillarity.
4. Which of the following is the correct name for that force which causes water molecules to attract each other? (*a*) Surface tension; (*b*) adhesion; (*c*) cohesion; (*d*) stress.
5. Which of the following is the correct name for that force which causes glass molecules and water molecules to attract each other? (*a*) Adhesion; (*b*) cohesion; (*c*) strain; (*d*) capillarity.
6. Which of the following terms is the correct reason why oil goes between sliding surfaces of machine bearings? (*a*) Capillarity; (*b*) surface tension; (*c*) diffusion.
7. Which of the following terms is the correct reason why free liquids assume a spherical shape? (*a*) Adhesion; (*b*) capillarity; (*c*) surface tension.

COMPLETE THESE STATEMENTS

On a separate sheet of paper numbered from 1 to 6 write the words needed to fill correctly the blank spaces in the following sentences.

An ..(1).. is a substance added to water to lower its freezing point. Boyle's law states that, if temperature is constant, the volume of a given weight of a gas varies ..(2).. with the pressure. If the speed of a fluid passing through a tube increases at any point, the pressure of the liquid decreases at that point. This is known as ..(3)... A ..(4).. tube is one which has a constriction in it. The high velocity of the air moving past the upper surface of an airplane wing produces ..(5).. pressure against that surface. The ..(6).. of a gasoline engine makes use of the Venturi tube.

Are These True or False?

On a separate sheet of paper numbered from 1 to 6 write a T *or an* F *to show whether each statement is true or false.*

1. The kinetic theory of matter assumes that the molecules of all matter are in constant motion.
2. Mercury does not wet the finger because adhesive force is greater than cohesive force.
3. Diffusion of liquids is faster than that of gases.
4. Within the elastic limit of a substance, strain is directly proportional to stress.
5. Liquids and gases are perfectly elastic.
6. The amount of gas that can be absorbed, or dissolved, by a liquid is inversely proportional to pressure.

QUESTIONS

1. Why is osmosis of gases and liquids so important?
2. Why doesn't the carbon dioxide of the air collect near the floor of a room?
3. Why does putting salt on a garden snail or slug cause it to become wrinkled?
4. If a noncorrosive liquid is to be introduced into the eye, why should it have the same density as the fluids inside the cell walls?
5. Explain the action of a towel in drying the hands.
6. Why is a paper that is to be used with ink covered with sizing?
7. When a glass rod is cut off, its edges are very sharp. Why do they become rounded when they are held in the flame until the glass is softened?
8. Shot are made by pouring molten lead on sieves supported at great height, from which drops of molten lead fall into a vessel of water. Why are the shot rounded?
9. A blacksmith welds two pieces of iron together by heating the ends, lapping them, and then pounding them on an anvil. Explain the principle involved.
10. Chemists hold a glass rod against the side of a beaker from which a liquid is being poured. What is its function?
11. Why is a pen to be used for writing with ink split at the point?

12. Is the air inside a soap bubble denser or rarer than the air outside? Explain.

13. Fish die in an aquarium unless the water is frequently renewed. Explain.

14. Why does effervescence occur when soda water is drawn from a soda fountain?

15. Water drawn from the hot-water tap quite often appears milky. Explain.

16. What principle of physics does a dentist use when he taps successive layers of gold foil into the cavity of a tooth?

17. What precautions should be taken in storing foods in a refrigerator?

18. What is meant by the term *Brownian movement?*

19. What are some of the most striking proofs of the molecular motion of gases?

20. Why is blotting paper effective in taking up excess ink? Is the use of sand similar in principle?

21. Why does a chimney "draw" better on a windy day? Why should the top of the chimney be higher than any part of the roof of a building?

22. Besides the Bernoulli principle what other factor aids the action of an atomizer?

23. Would high altitude have any effect upon the action of a carburetor? Explain.

PROBLEMS

1. A wire 1 mm. in diameter is stretched 0.1 mm. by a certain weight. How far will a wire 3 mm. in diameter be stretched by the same weight if it is of the same material and of equal length?

2. Two wires have the same diameter. One is 1 ft. long, and the other is 10 ft. long. If it takes a force of 10 lb. to break the first wire, what force will be needed to break the second one?

3. If you were given a coiled spring, a metal frame, a ruler, one weight of 1 gm., and another of 10 gm., how would you proceed to make a spring balance that would weigh up to 250 gm.?

4. Upon a spring balance, the ounce marks are 1 mm. apart. How long a scale will be needed if the balance is to be used for weighing 10 lb.?

5. One liter of ice-cold water absorbs 1.7 gm. of carbon dioxide when it is under a pressure of 1 atmosphere. How many gm. of carbon dioxide can be absorbed under a pressure of 6 atmospheres?

6. What will be the weight of 1 liter of air in a tire that is inflated to a pressure of five atmospheres? (1 liter at 1 atmosphere weighs 1.293 grams.)

7. A football has a volume of 250 cu. in. If it is inflated to a pressure of six atmospheres, what volume will the air inside occupy when released at a pressure of one atmosphere?

8. The volume of a given mass of gas is 1200 cc. when the barometer reads 840 mm. What volume will the gas occupy when the pressure is reduced to 750 mm.?

9. Remembering that VP = a constant, what successive pressures will be needed to change 800 cc. of gas at 400 mm. to the following volumes? 1200 cc.? 200 cc.? 1600 cc.? 100 cc.? 2400 cc.?

10. Suppose that you have 200 cu. ft. of oxygen gas under a pressure of 1 atmosphere. What pressure will be needed to crowd the gas into a container whose volume is 10 cu. ft.?

11. At a pressure of 1 atmosphere, 1 liter of oxygen weighs 1.43 gm. What will be the weight of 1 liter of oxygen under a pressure of 10 atmospheres?

VII

Machines Apply Forces

A. FORCE OF GRAVITATION

What makes bodies fall? We have already defined force as a "push" or a "pull" and weight as the measure of the earth's attraction for a body. Now we need to define gravitation. Before a child learns to walk, he experiences the force of gravitation. He finds that bodies fall toward the earth. He cannot tell why, and neither can anyone else. We say that bodies fall toward the earth because they are attracted by *gravity,* or that most common of all forces, *gravitation.*

Sir Isaac Newton called attention to the fact that gravitation is *universal,* and also that the attraction between bodies is *mutual.* The force is *universal* because it applies to the earth, the sun, the stars, and all bodies in the universe. It is *mutual,* because an apple attracts the earth, as well as being attracted by the earth. The earth attracts the moon, and the moon also attracts the earth.

1. LAW OF GRAVITATION

Newton's formula. The magnitude of the force of mutual attraction depends upon two things: (1) The masses of the bodies; (2) the distance between their centers. It takes twice the force to lift two bricks that it does to lift one, because we must overcome the earth's attraction for twice as much mass. The saying that "distance lends enchantment" does not apply to the mutual force of gravitation, because the force of attraction between two bodies decreases as the square of the distance between their centers increases. Newton did not discover gravitation, but he formulated the following law: *Every body in the universe attracts every other body with a force that is directly proportional to the* *product of their masses and inversely proportional to the square of the distance between their centers.* An object at the surface of the earth is about 4000 miles from its center. If it were taken up to a height of 1000 miles, it would then be 5000 miles from the earth's center. The earth's attraction for it would then be only 16/25 as much as before. $(4000)^2 \div (5000)^2 = 16/25$. A body that weighs 100 lb. at the earth's surface will weigh only 64 lb. at a height of 1000 miles above the surface.

2. MEANING OF WEIGHT

Weight depends on gravitational force. We have already several times defined the weight of a body as the measure of the earth's attraction for that body. When we say that a man weighs 200 lb., we mean that he attracts the earth with a pull of 200 lb., and that the earth's attraction for him is equal to 200 lb. Since all parts of the earth's surface are not equidistant from its center, we should expect the weight of an object to vary in different localities. For example, a body will weigh slightly less on top of a mountain than it does in a valley. Since the earth is slightly flattened at the poles, a man will weigh slightly more at the North Pole than he does at the equator. A man who weighs 189 lb. at the equator weighs about 190 lb. at either pole.

If a hole were bored down into the earth and a body were lowered into it, its weight would not keep increasing as it descends beneath the surface. It is true that it would be getting nearer the earth's center, but the gravitational pull of the material above it would cause it to weigh less when it was *beneath* the surface. A body will have its greatest weight *on that part of the surface* which is nearest the earth's center, but it will lose in weight if carried above the surface or lowered beneath it.

The mass of the sun is so much greater than the mass of the earth that an object which weighs 100 lb. on the earth would weigh at the surface of the sun about 2700 lb. The force of gravitation on the moon is so much smaller than it is on the earth that a person on the moon would weigh only about one-sixth as much as he does on the earth. An athlete on the moon could easily jump from 25 to 30 ft. high, but on the sun he would be unable to lift his foot.

3. GRAPHIC REPRESENTATION OF FORCE

How may we picture forces? Since a force has both magnitude and direction, we may use a straight line to represent a force. It is also necessary to consider the point at which the force is applied.

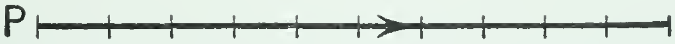


Fig. 7–1. A line is used to represent a force.

Suppose, for example, that we wish to represent a force of 10 lb. acting in an easterly direction upon the point P. We may use a straight line ten units long, drawn in an easterly direction from the point P. (See Fig. 7–1). Any *convenient* unit may be selected, but it is necessary to use the same unit if several forces are represented on the same diagram. We may let $\frac{1}{4}$ in. represent 1 lb., or 1 mm. represent 1 lb., or use any other scale we wish. The choice of the unit will depend upon the amount of space available for the diagram.

In Figure 7–2, we have two forces represented; one force of 15 gm. acts in a westerly direction upon the point P; the other, a force of 20 gm., acts in a southerly direction upon the same point.

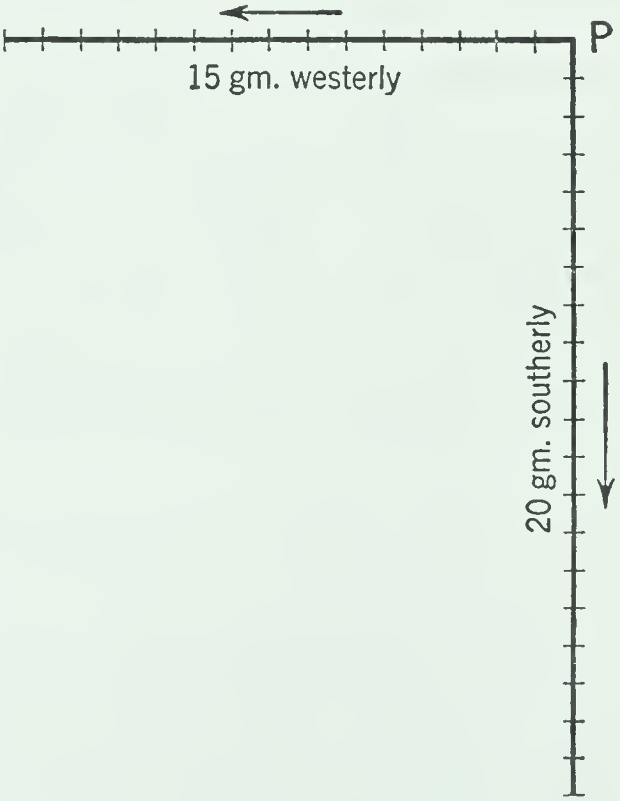


Fig. 7–2. Representation of two forces acting at an angle.

Demonstration. Hook two spring balances together and pull in opposite directions until the right-hand balance reads 100 grams. What is the reading of the left-hand balance? Construct a diagram of these two forces by letting 1 cm. represent 10 gm. Draw a line with an arrow pointing to the right, representing the right-hand balance reading. Extend this line, with an arrow pointing to the left, representing the left-hand balance reading. Compare the lengths of these two line segments. Could a tug of war be represented by such a force diagram?

B. COMPOSITION OF FORCES

What is a resultant? Quite often two or more forces act simultaneously upon the same point. Sometimes we wish to find the point of application, magnitude, and direction of a *single* force that could produce the same effect as all the forces acting conjointly. *The resultant of two or more forces is that single force which could produce the same effect as the two or more forces acting together.*

The resultant of two or more forces is really a *substitute* for those forces. When the football coach sends a substitute into the game, he removes one player from the field. If we use the resultant or substitute force, we assume that it takes the place of two or more forces. After we have found their resultant, the separate forces need no longer be considered. Unlike the football substitute, who does not always produce the same effect as the man displaced, the resultant force must produce *exactly the same effect* as *all* the forces for which it is substituted.

1. FORCES ACTING IN THE SAME DIRECTION

What is their resultant? If we have one boy pulling on a rope with a force of 40 lb., and another boy joins him and pulls in the same direction with a force of 60 lb., the resultant in this case is equal to the *sum of the two forces.* If the boys stopped pulling, one man taking their place could produce the same effect by pulling in the same direction with a force of 100 lb.

2. FORCES ACTING IN OPPOSITE DIRECTIONS

What is their resultant? If one boy pulls in one direction with a force of 40 lb., and another boy pulls in the opposite direction with a force of 60 lb., then the resultant is the *difference between the two forces.* In this case a force of 20 lb. pulling in the direction of the *greater* force would produce the same effect.

3. FORCES ACTING AT ANGLES TO EACH OTHER

How do we calculate the resultant of forces acting at right angles? Suppose that one force of 10 gm. acts in an easterly direction upon an object at point A, Figure 7–3, and another force of 15 gm. acts in a southerly direction upon the same point. Let us first plot the two forces. It is obvious that the first force acting alone tends to move the object along AB to B. The second force acting alone tends to move the object along AC to C. If the two forces acted *successively* upon the object it would arrive at point D; if they act *simultaneously,* it would also arrive at point D, but its line of motion would be along the diagonal of the parallelogram of which the two forces are sides. *The resultant of two forces acting at an angle upon a given point is equal to the diagonal of a parallelogram of which the two forces are sides.* Students of geometry know that the sum of the squares of the two sides of a right triangle equals the square of the hypotenuse. If we extract the square root of the sum of the squares of the two sides of the parallelogram, we can calculate the resultant. In the above example, $\sqrt{(10)^2 + (15)^2} =$ 18+ gm.

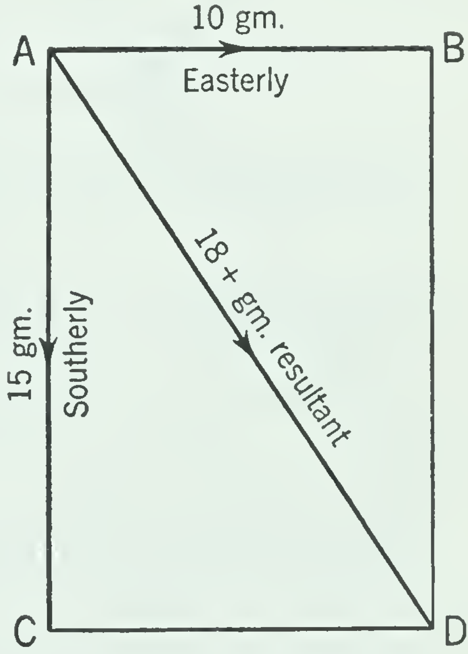


FIG. 7–3. Parallelogram of forces.

DEMONSTRATION. Construct a force diagram for a force of 100 lb. acting east and a force of 150 lb. acting south. (See Fig. 7–3.) Use a protractor or a compass to make sure the angle at which the two forces act on a point is a right angle. Complete the parallelogram and draw the diagonal (*resultant*). Find the magnitude of the resultant in pounds by both scale measurement and computation.

How do we calculate the resultant of forces acting at any angle? It more often happens that the angle between two forces acting upon the same point is not a right angle. In Figure 7–4, we have represented forces of 10 gm. and 15 gm. respectively, acting upon the point *A*. In this case the angle between the two forces is only 50°. Unless the student knows trigonometry, he cannot *calculate* the resultant of these two forces acting at this angle. To find the approximate value of the resultant, we draw a parallelogram, using the two forces *AB* and *AC* as sides. We must make the angle between them 50°. From the point *A* we draw a diagonal and measure it carefully. From the length of the diagonal, we find the equivalent of the resultant force in grams.

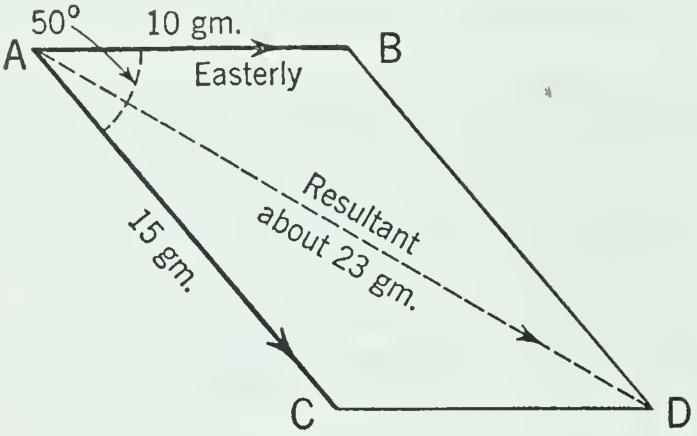


FIG. 7–4. Resultant of two forces acting at an acute angle.

We find that the resultant is decidedly different if we use the same two forces, but make the angle between them 140°. The parallelogram is constructed in the same manner, using the forces as sides, and making the angle between them 140°. (See Fig. 7–5.) Of course the diagonal must be drawn from *A*. The resultant could never produce the same effect as the two forces acting at

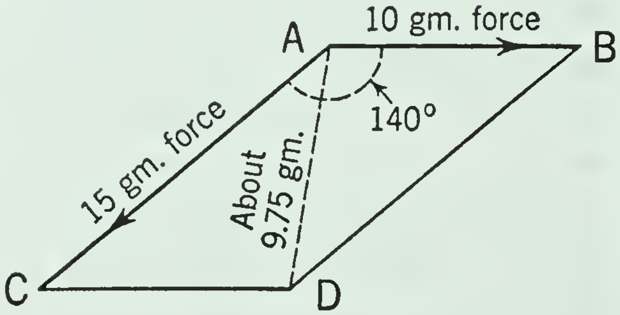


FIG. 7–5. Resultant of two forces acting at an obtuse angle.

A if it were applied at *B*. Beginners sometimes make the mistake of drawing the wrong diagonal as the resultant. The diagonal is measured and its value determined as before.

Sometimes three or more forces act at different angles upon the same point. It is possible to find their resultant by finding first the resultant of two of them, using them as sides of a parallelogram, and finding the diagonal. Then we can construct another parallelogram, using as sides the third force and the diagonal of the first parallelogram. The diagonal of the second parallelogram is the resultant of the three concurrent forces.

What is the equilibrant? Sometimes it is desirable to find the point of application, magnitude, and direction of a force which could be applied *to produce equilibrium*, or *to prevent motion*. A boy pulls on a wagon with a force of 40 lb. A second boy pulls on the wagon with a force of 40 lb. in exactly the opposite direction. He prevents motion, or produces equilibrium. The force he uses is called the *equilibrant*.

It is quite as easy to find the equilibrant of two or more forces acting upon a point. We must first find their resultant and then apply the equilibrant in an opposite direction. In Figure 7–3, we found that a single force, 18+ gm., can be substituted for the two forces *AB* and *AC*. By removing the two forces, and leaving their resultant *AD*, we find that the equilibrant force represented by *AE must be applied at the same point A, its direction must be directly opposite to that of the resultant, and its magnitude must be equal to the magnitude of the resultant.* (See Fig. 7–6.) Hence we conclude that *the equilibrant of two or more forces is always equal and opposite to their resultant.*

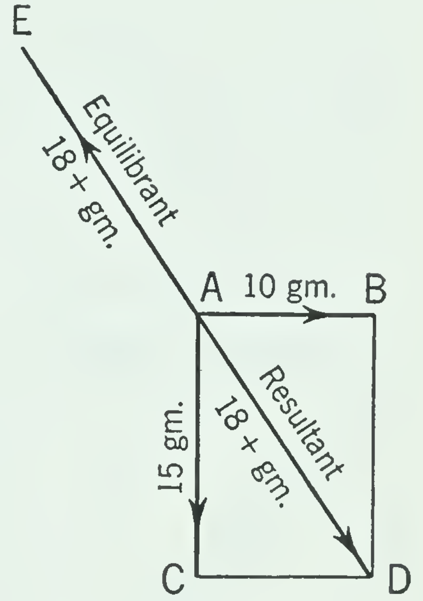


FIG. 7–6. The equilibrant prevents motion.

C. RESOLUTION OF FORCES

How may we resolve forces? We have just learned how to find a single force that could produce the same effect as two *component* forces. When the forces acted at an angle, our problem became one of a simple construction in geometry: given the two sides and the included angle of a parallelogram, to construct the parallelogram and draw its diagonal.

Now if we have given the resultant of two forces acting at an angle, one of the forces, and the angle included between that force and the resultant, we should be able to find the value of the other force. Our problem in this example of *resolution* of forces is the converse of that in *composition* of forces. We have given the diagonal of a parallelogram, one of the sides, and the angle between that side and the diagonal. The problem is to construct the parallelogram and find the other side.

Problem. Two forces act upon the point *A;* one force of 8 gm. acts in a southerly direction; an unknown force acting at an angle with the 8-gm. force produces the same effect as a single force of 10 gm., acting in a direction 37° east of south. Find the magnitude and direction of the unknown force.

Solution. Construct a parallelogram, using for one side the 8-gm. force, *AB*, acting southerly. (See Fig. 7–7.) Using a protractor, measure off an angle of 37°, east of south, and draw a line *AC* to represent the resultant force, 10 gm. Use this resultant force as the diagonal of a parallelogram and construct the parallelogram. The side *AD* of the parallelogram is the unknown force.

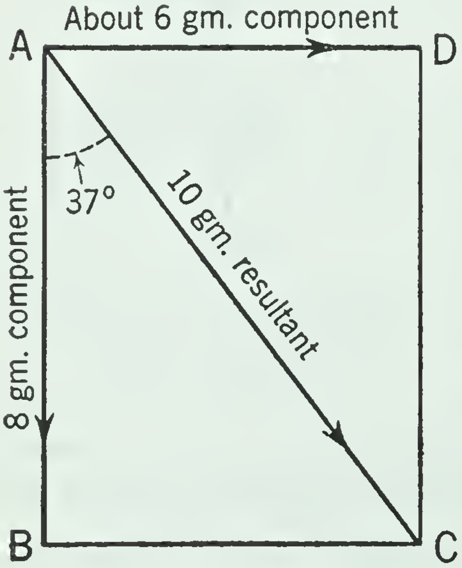


Fig. 7–7. The horizontal component of the force is 6 gm.

How is the force of gravity resolved? *Inclined Plane.* It quite often happens that a force acts upon an object in a direction in which the object is not free to move. Such a force may be resolved into two components. An object resting upon an inclined plane is acted upon by gravity with a force equal to its weight. (See Fig. 7–8.) The plane prevents the motion of the object in the direction *OW*, but this resultant force *OW* may be resolved into two components. One component, *OD*, acts perpendicular to the surface of the plane, and tends to break the plane. The other force, *OR*, acts parallel to the plane, tending to pull the object down the plane.

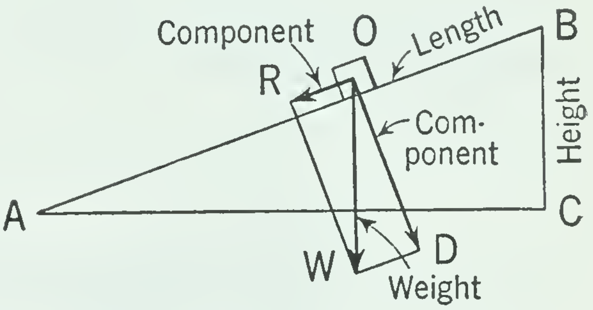


FIG. 7–8. Resolving a vertical force into its components.

Upon the diagonal *OW*, we may construct the parallelogram *ORWD*, and find the *relative* values of the sides *OR* and *OD* by plotting to scale. In this special case, we can calculate these values if the height and length of the plane are known. The triangles *ABC* and *WOR* are similar. (The sides are mutually parallel and perpendicular.) Hence, *OR* : *OW* = *BC* : *AB*. But *OR* represents the force or effort, *E*, tending to pull the object down the plane; *OW*, the weight or resistance, *R*, of the object; *BC*, the height of the plane; and *AB*, the length of the plane. Hence, the effort bears the same relation to the *resistance* that the height of the plane does to its length. Or:

$$E:R = h:l$$

In the same manner it may be shown that the force tending to break the plane bears the same ratio to its weight that the base of the plane does to its length.

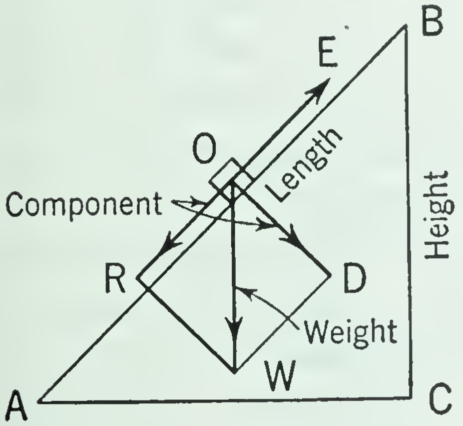


FIG. 7–9. Component parallel to plane increases as we make the plane steeper.

Making the plane steeper increases the force *OR* in proportion to the weight and decreases the force *OD*. (See Fig. 7–9.) The force *OE*, which is equal and opposite to *OR*, represents the effort needed to keep the object from sliding down the plane. The steeper the plane, the greater this force becomes.

Some other applications of resolution of forces. When you push a lawn mower, you wish the mower to move along the surface of the ground, but you push at an angle to the ground because it is more convenient. (See Fig. 7–10.) The force that you apply is resolved into two components. One component pushes the mower forward parallel with the lawn; the other acts perpendicularly and it tends to push the mower into the ground. Suppose that you push with a force of 80 lb. at the angle shown in the figure. By constructing a parallelogram to scale, we find that the horizontal component is about 74 lb.; the vertical component, which tends to push the mower into the ground, is approximately 31 lb.

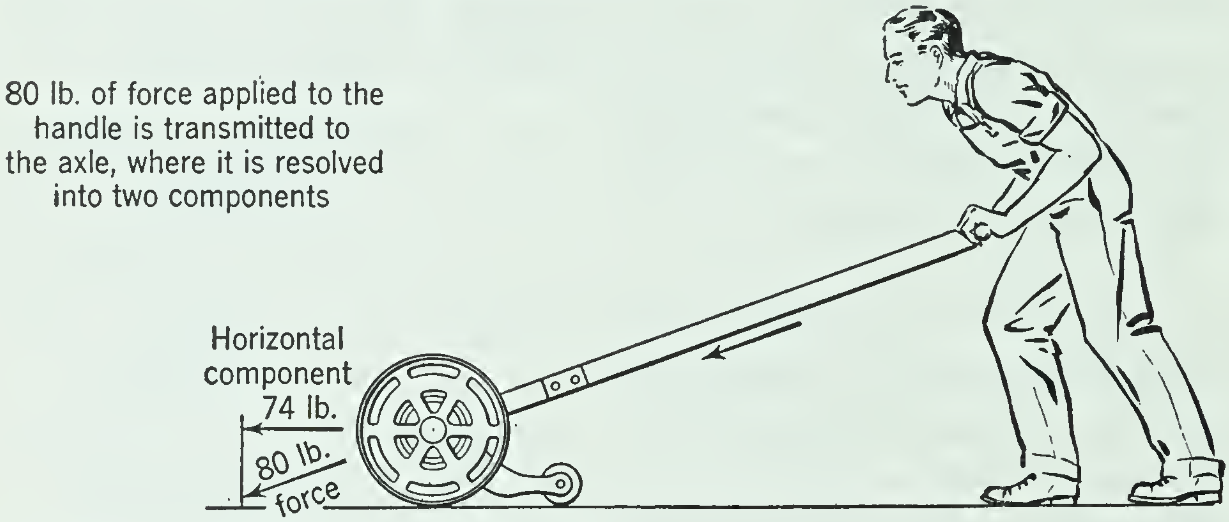

80 lb. of force applied to the handle is transmitted to the axle, where it is resolved into two components

Fig. 7–10. The force applied to the handle of the mower is resolved into two components.

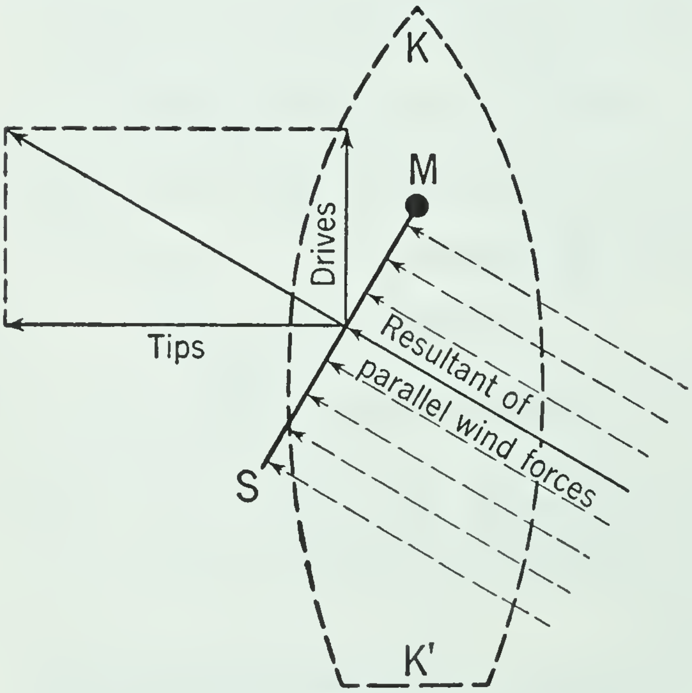


Fig. 7–11. The wind acts against the sails and is resolved into two components.

When a boy pulls a loaded sled, the force which he exerts is resolved into two components. The horizontal component draws the sled forward; the vertical component tends to lift the sled vertically.

When a sailboat is moving with the wind, the full force of the wind drives the boat forward. When the boat is moving at an angle with the direction of the wind, part of the force of the wind drives the boat forward, and the other component *tips* the boat. (See Fig. 7–11.)

In the case of the guy wire on a telephone pole, one component tends to pull the pole into the ground, and the other acts horizontally. When a switch engine on one track pushes a freight car on a parallel track, the thrust force is resolved into two components. One component moves the car along the track, while the other component tends to spread the rails apart. (See Fig. 7–12.) In the builder's crane or in the steam shovel, the boom must be stiff enough to resist by a thrust force the combined effect of the weight on the rope or chain and the tie force. If the thrust force and the weight are known, the value of the tie force may be found. (See Fig. 7–13.) In a house or barn, the weight of

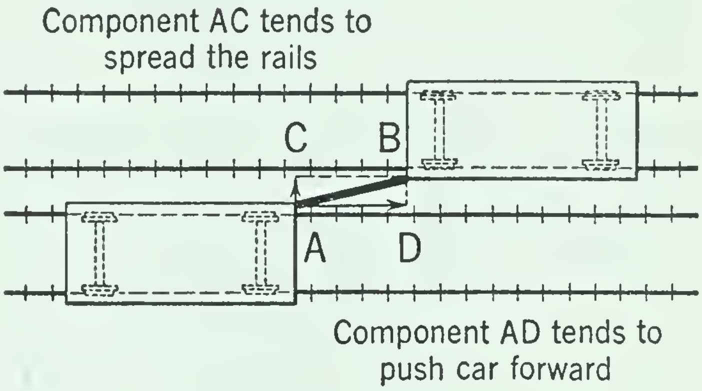

Component AC tends to spread the rails
C
B
A
D
Component AD tends to push car forward

Fig. 7–12. The force *AB* is resolved into two components.

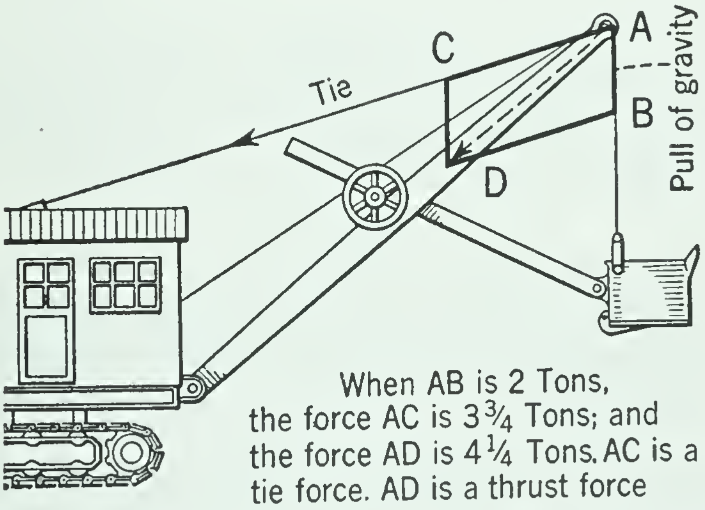

A
C
Tie
B
D
Pull of gravity
When AB is 2 Tons, the force AC is 3¾ Tons; and the force AD is 4¼ Tons. AC is a tie force. AD is a thrust force

Fig. 7–13. How forces are resolved in a steam shovel.

the roof acts downward and outward upon the walls of the house. By reference to Figure 7–14, we can see how the weight of the roof is resolved into the two components. To support a weight *OW* applied at *O*, the combined upward thrusts *OM* and *OS* of the rafters must produce a resultant force *OR* equal to *OW*.

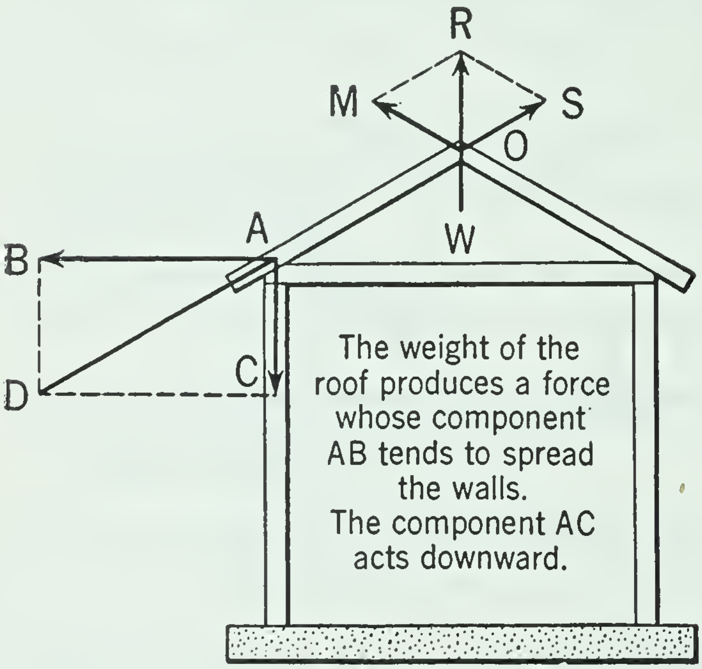

R
M
S
O
W
A
B
D
C
The weight of the roof produces a force whose component AB tends to spread the walls.
The component AC acts downward.

Fig. 7–14. The weight of the roof pushes downward and also tends to spread the walls.

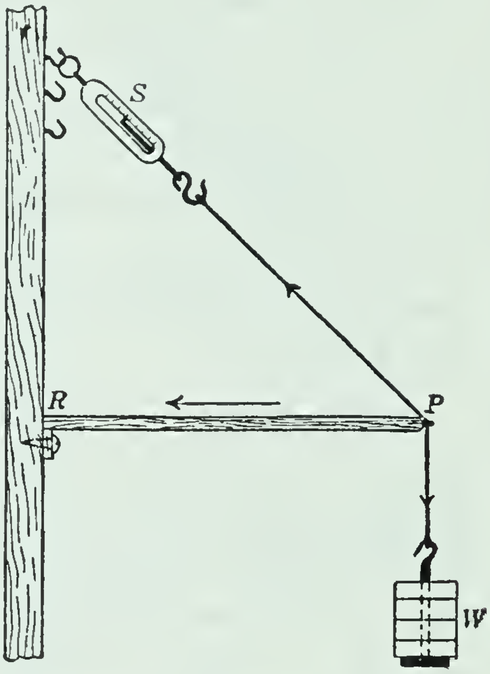


Fig. 7–15. A simple crane boom.

Demonstration. Set up a simple crane boom as in Figure 7–15. Use a 500-gm. weight for *W*. Note the balance reading at *S*. Hook a second balance to the end of the boom at *P* and measure the force necessary to move it horizontally to the right. With a protractor measure the angle *RPS*.

Construct to scale a parallelogram showing how the 500-gm. weight is resolved into the two forces just measured by the balances. (See Fig. 7–15.)

D. TYPES OF MOTION

1. DEFINITION OF MOTION

We may define motion as a change of place or position. Both motion and rest are *relative* terms. A person may be riding uptown on one of the express trains of a New York subway. He is in motion with respect to an object on the station platform, but he is at rest with respect to others on the train. His train is passing an uptown local, to which the motion of his train is relative. There is a different example of relative motion, if we compare the motion of the uptown express with that of a downtown express or a downtown local. We appear to be at rest upon the surface of the earth, but as the earth rotates on its axis, we are carried with it at a speed of possibly 1000 miles per hour. We also travel with the earth in its path around the sun, a distance of a little more than 1,600,000 miles per day, at a speed of a little less than 70,000 miles per hour.

If an object moves in a straight line, its motion is said to be *rectilinear;* if the object moves along a curved line, its motion is *curvilinear.*

2. VELOCITY

Velocity is defined as the rate of motion. The velocity of an object is the distance it moves in a given unit of time. It may be expressed in feet per second, miles per hour, or kilometers per hour. At a brisk walk we travel at a velocity of 5 or 6 ft. per sec., or about 4 mi. per hr. A sprinter runs at the rate of 30 ft. per sec.; a train runs at a velocity of 60 mi. per hr. or 88 ft. per sec. A rifle bullet may have a velocity of 3000 ft. per sec. The word "speed" is almost synonymous with the term "velocity," and they are often used interchangeably, although velocity more properly applies to the rate of motion *in a given direction.*

Motion is *uniform* when the velocity is constant, or when the distance a body moves is the same for each succeeding unit of time. A car that *maintains* a velocity of 30 mi. per hr. is an example of uniform motion. If a car travels 40 mi. the first hour, 20 mi. the second hour, and 30 mi. the third, its motion is *variable.* The distances it travels in equal periods of time are unequal.

As a matter of fact, automobiles, trains, airplanes, and various other means of transportation do not maintain constant velocity for any great period of time. Automobiles and trains have to climb hills, negotiate curves, and make necessary stops. Airplanes meet various wind and weather conditions. So do boats. It is therefore more meaningful to speak of *average velocity.* The car mentioned in the preceding paragraph traveled a total of 90 miles (40 + 20 + 30) in three hours; therefore its average velocity for the three-hour period was 30 miles per hour (90 ÷ 3). In order to make a 700-mile run in 14 hours, a train must maintain an average speed of 50 miles per hour.

$$\textbf{Average speed or velocity} = \frac{\textbf{total distance}}{\textbf{time}}$$

3. ACCELERATION

Acceleration is increase in velocity. The word *accelerator* has grown more and more common with the increased use of the automobile. A man is driving at a velocity or speed of "30 miles per hour." He presses the accelerator, and increases his velocity to "40 miles per hour." He has *added to* his velocity "10 miles per hour." Such an *increase in velocity is called acceleration.* When a manufacturer advertises that his car will "accelerate from 5 miles per hour to 25 miles per hour in 8 seconds," he means that in 8 seconds 20 miles per hour can be added to the velocity of the car. That is an addition, or acceleration, of 2.5 miles per hour per second. A body that moves 1 ft. the first second, 3 ft. the next second, 5 ft. the third second, etc., furnishes an example of *accelerated motion.* In each second the velocity *increases* 2 ft. per second, and we say that the acceleration is 2 ft. *per second per second.* If a car moves 1 mi. per hr. the first second, 3 mi. per hr. the next second, and 5 mi. per hr. the third second, the increase in velocity for each second is 2 mi. per hr.; the acceleration is 2 mi. *per hr. per second.* Since in both of the examples given the acceleration is constant, the motion is *uniformly* accelerated. A body that moves 2 ft. the first second, 5 ft. the next second, and 10 ft. the third second is also an example of accelerated motion, but the acceleration is *not uniform;* it is *variably* accelerated motion.

In stopping, a vehicle may move 7 ft., 5 ft., 3 ft., and 1 ft. in each of four *successive seconds.* This is an example of *negatively accelerated* motion. It is also known as *retarded* or *decelerated* motion. Since in each second 2 ft. per second are *subtracted* from its velocity, its motion is *uniformly* retarded.

It is possible, too, to have *variably* retarded motion. We have an example of such motion when a reckless or unskilled driver rushes up to a red light and then stops with a screeching of brakes and tires.

How can we find the velocity at any given time? It is of interest to inquire what would happen if the acceleration stopped at the end of any *particular* second. For example, a car in starting moves 5, 10, 15, and 20 ft. per sec. for four successive seconds. Then the operator takes his foot off the accelerator. What happens? If we neglect friction, the car continues to move on at the *uniform* velocity of 20 ft. per sec. In accelerated motion, where the velocity varies each second, *the velocity at the end of any particular second is equal to the distance the body would move during the next second, if at that instant it ceased to be accelerated.*

What are the laws of accelerated motion? Aristotle taught that the rate of fall of bodies was proportional to their weights. He said that a bundle of two bricks would fall twice as fast as a single brick. He did not experiment, and this false idea persisted for centuries. But Galileo was an experimenter. He dropped from the top of the leaning tower at Pisa objects of different material and found that they all reached the ground at nearly the same time. (See Fig. 7–16.) Even paper fell rapidly when rolled into a compact ball. Then Galileo used an inclined plane to study accelerated motion by rolling balls down the plane. A ball rolls down an inclined plane with uniformly accelerated motion, but the distance traveled in any number of seconds is so much less than that of freely falling bodies, that the distance can be more easily measured.

If we were to repeat Galileo's experiments by letting a ball roll down a grooved plane which is made just steep enough so that the ball rolls 1 ft. the first second, we should obtain results about as follows (see Fig. 7–17):

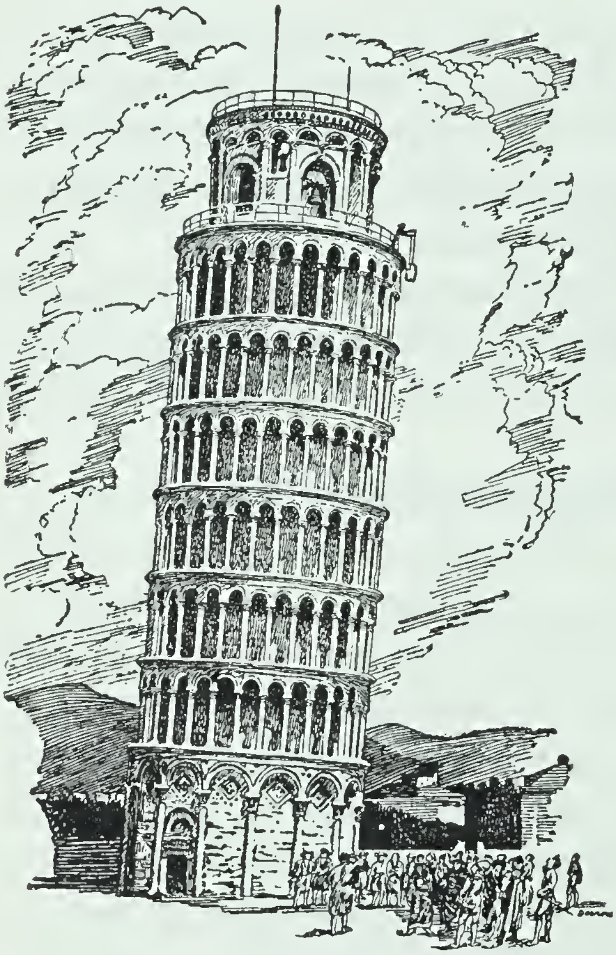
The ball rolls

1 foot in 1 second;
4 feet in 2 seconds;
9 feet in 3 seconds;
16 feet in 4 seconds;
25 feet in 5 seconds.

Thus we see that the distance the ball rolls is directly proportional to the square of the number of seconds. It is also easy to deduce the following observations:

The ball rolled

1 foot the *first* second;
3 feet the *second* second; (4–1)
5 feet the *third* second; (9–4)
7 feet the *fourth* second; (16–9)
9 feet the *fifth* second. (25–16)



Courtesy of Popular Science Monthly

FIG. 7–16. The leaning tower at Pisa, Italy, was the scene of some of Galileo's famous experiments.

The figures 1, 3, 5, 7, and 9 show that the motion was *uniformly* accelerated; the acceleration, a, is 2 feet per second for each second of time. Since velocity is the *rate* a body moves in a given time, and since acceleration is the *change in rate* for a given time, it is correct to use the term acceleration per second per second (rate per second of change of velocity), or acceleration per hour per hour. To avoid apparent repetition, the term "acceleration per second" may be used when both the velocity and acceleration are rated in seconds. When a body starts from rest and travels with uniformly accelerated motion, *the acceleration equals twice the distance traversed during the first second.*

The *initial* velocity of the ball was zero; its acceleration, or gain in velocity, was 2 ft. per sec.; therefore its velocity at the *end* of the first second was 2 ft. per sec. At the end of the next second, its velocity was 4 ft. per second. In five seconds, 5 × 2, or 10 ft. per sec. will have been added to its original velocity. Its velocity at the end of the fifth second is 10 ft. per sec. Thus we find that in each case, the final velocity is equal to the *product of the acceleration by the time.*

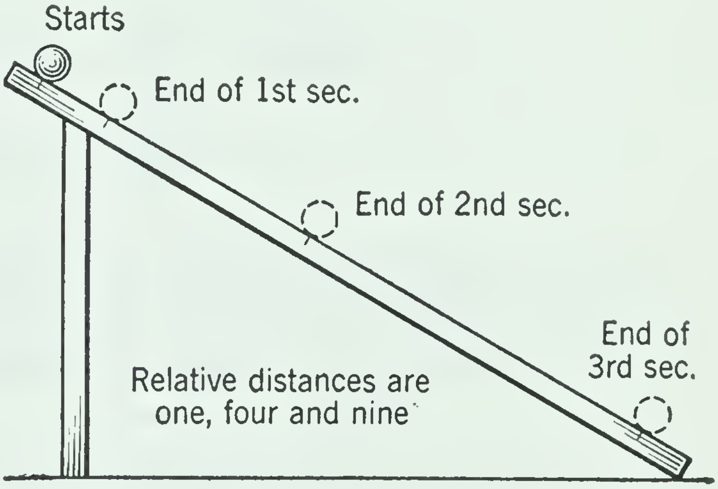


FIG. 7–17. The ball gains velocity as it rolls down the plane.

From the simple observations given above, we deduce several laws that apply to all cases of uniformly accelerated motion.

LAW 1. *If the acceleration is uniform, the velocity at the end of any second is directly proportional to the time.*

Using v to represent *final* velocity, a to represent acceleration, and t to represent time, we may express this statement algebraically; *final velocity equals acceleration times the time.*

$$v = at \quad \text{(Formula 1)}$$

In all types of motion, the total space passed over, S, equals the *average* velocity times the number of seconds, t:

$$\text{distance} = \text{average velocity} \times \text{time}$$

The average velocity for any given number of seconds equals one-half the sum of the initial and final velocities:

$$\text{average velocity} = \frac{\text{initial velocity} + \text{final velocity}}{2}$$

For a body starting from rest, the initial velocity is zero; the final velocity equals *at*; from these values the second law may be derived:

$$\text{average velocity} = \frac{\text{zero} + at}{2}$$

We get by substitution in the formula, distance = average velocity × time, the following:

$$\text{distance} = \frac{at}{2} \times t, \text{ or}$$

$$S = \frac{1}{2}at^2 \quad \text{(Formula 2)}$$

LAW 2. *If the acceleration is constant, the distance traversed in any given number of seconds is equal to one-half the acceleration times the square of the number of seconds.*

In solving problems, we may use formula 1 to find v, a, or t, if two of these quantities are known. If any two of the following, a, t, and S, are known, the third may be found by the use of formula 2. Given a, v, and S; any two of them known, and the third to be found. Solving formula 1 for t, and substituting in formula 2 the value thus obtained, we get:

$$v = \sqrt{2aS} \quad \text{(Formula 3)}$$

The formula, $s = \frac{1}{2}a(2t - 1)$, may be used to find the distances traversed in any *given* second, the *sixth* or *eighth*, for example.

PROBLEM. A ball starting from rest rolls down an inclined plane with uniformly accelerated motion. If its acceleration is 20 ft. per second per second, find: (1), its velocity at the end of the tenth second; (2), the distance it travels in 10 seconds; and (3), the distance it rolls in the eighth second.

Solution. To find the final velocity, we use the formula, $v = at$. Therefore, $v = 20 \times 10$, or 200 ft. per second. By substituting in the formula, $S = \frac{1}{2}at^2$, the values for a and t, we have $S = \frac{1}{2} \times 20 \times (10)^2$. $S = 1000$ ft. To find the distance the ball rolls in the eighth second, we use the formula $s = \frac{1}{2}a(2t - 1)$.

$$s = 10[(2 \times 8) - 1] \quad s = 150 \text{ ft.}$$

Alternative solution. The final velocity is found from the formula $v = at$. Whence, $v = 200$ ft. per sec. The initial velocity is zero and the final velocity is 200 ft. per sec. The average velocity is 100 ft. per sec. In 10 seconds, the ball will roll 10 × 100 ft., or 1000 ft. In 8 seconds the ball rolls at an average velocity of 80 ft. per sec., a distance of 640 ft. In 7 seconds, the average velocity was 70 ft. per sec., and the distance 490 ft. In the *eighth* sec. it must have rolled the difference,

$$640 - 490 = 150 \text{ ft.}$$

DEMONSTRATION. On the edge of an 8-ft. board about 2 in. wide nail strips of lath to make a shallow trough so that a small steel ball can roll freely in it. Mark the board at every 6 in. of its length, thus dividing the length into 16 equal parts. Tilt the board at such an angle as will make a steel ball starting from the top of the incline reach the bottom in exactly 4 sec. While another person counts the seconds aloud, mark with chalk the position of the ball at the end of each second as it rolls down the incline. How far did the ball travel in 1 sec.? 2 sec.? 3 sec.? 4 sec.? Compare the results with Fig. 7–17.

What are the laws for retarded motion? The laws and formulas given in the preceding section also apply to *uniformly* retarded motion. We use them when we wish to know how far a car will run before it can be stopped, or how long it will take to stop a car. Suppose that we have a car traveling 30 mi. per hr., or 44 ft. per

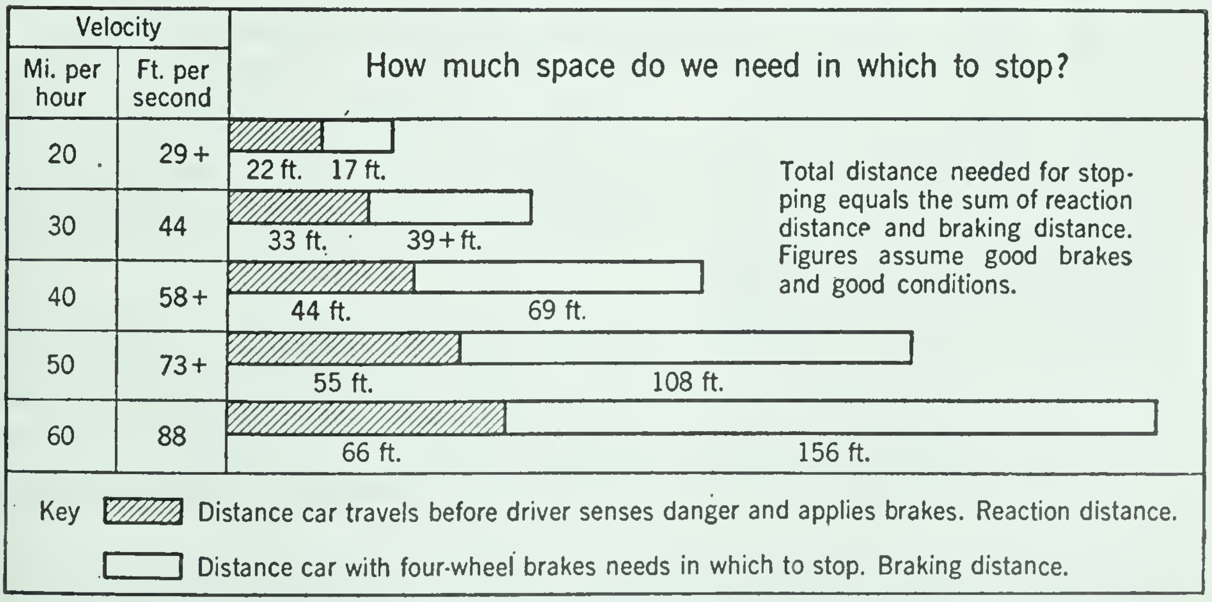


FIG. 7–18. Doubling of the velocity quadruples the distance needed in which to stop a car after the brakes have been applied.

sec.; the brakes are capable of retarding the car 10 ft. per sec. per sec. We wish to know how quickly the car can be stopped and how far it will travel after the brakes are applied. Our problem is solved in exactly the same manner as if we asked how far a car must travel to attain a speed of 30 mi. per hr. if the acceleration is 10 ft. per sec. per sec., and how long it will take.

Solution. Velocity and acceleration are known; distance is to be found. These three quantities all occur in formula 3.

$$\begin{aligned} v &= \sqrt{2aS} \\ 44 &= \sqrt{2 \times 10 \times S}, \text{ by substitution} \\ 20S &= (44)^2, \text{ and } S \text{ equals } 96.8 \text{ ft.} \end{aligned}$$

To find the time, we may use $v = at$, and substitute $44 = 10t$, whence we find that $t = 4.4$, or we may substitute in the formula $S = \frac{1}{2}at^2$, using $S = 96.8$ ft. and $\frac{1}{2}a = 5$ ft. per sec. per sec. The result is the same, 4.4 seconds. (See Appendix C.)

The chart, Figure 7–18, shows the distances within which a car should be able to stop when traveling at different velocities. For your own safety, you should observe that a car needs *4 times the distance* in which to stop after braking if the velocity is *doubled.*

The laws of acceleration apply to freely falling bodies. If we make the plane used in repeating Galileo's experiments steeper, the acceleration increases. When the plane is vertical, the ball becomes a freely falling body. The acceleration is due to the continuous attractive force of gravity, but now it is not resolved into two components as before. (See Fig. 7–8.) The force of gravity pulls directly upon the ball.

We have learned that the gram of force, which is a gravitational unit, imparts to 1 gm. of mass a velocity of 980 cm. per sec. in one second of time at the latitude of New York. Since $v = at$, then, from the above definition, a is equal to 980 cm. per sec. per sec.

The laws of accelerated motion apply to freely falling bodies, but since the *acceleration due to gravity* is always the same at a given locality, the letter g is used instead of a to represent acceleration. For New York, $g = 980$ cm., or 32.16 ft. per sec. per sec. The formulas derived on pages 205–206 then become,

$$(1)\quad v = gt$$
$$(2)\quad S = \tfrac{1}{2}gt^2$$
$$(3)\quad v = \sqrt{2gS}$$
$$(4)\quad s = \tfrac{1}{2}g(2t - 1)$$

Objects fall at the same rate in a vacuum. When Galileo performed his celebrated experiments with falling bodies, he found that dense objects fell rather more rapidly than lighter objects. There was so little difference in the majority of cases that he concluded that the unequal rate must be due to the resistance of the air, and *that all bodies would fall at the same rate in a vacuum.*

The invention of the air pump made it possible to prove the correctness of Galileo's theory. A long glass tube, containing a feather and a coin, is inverted. The feather flutters down slowly, striking the bottom at a considerable interval after the coin. (See Fig. 7–19*A*.) When the air is pumped from the tube and it is again inverted, both fall simultaneously. (See Fig. 7–19*B*.) A man who weighs 200 lb. does not fall any faster than a man who weighs only 140 lb. A laboratory device known as the water hammer is sometimes used to demonstrate rapid fall in a vacuum. It consists of a glass tube partly filled with water; the air is removed and the tube sealed. When the tube is jerked suddenly, the water falls like a stone, producing a sharp click as it strikes the glass.

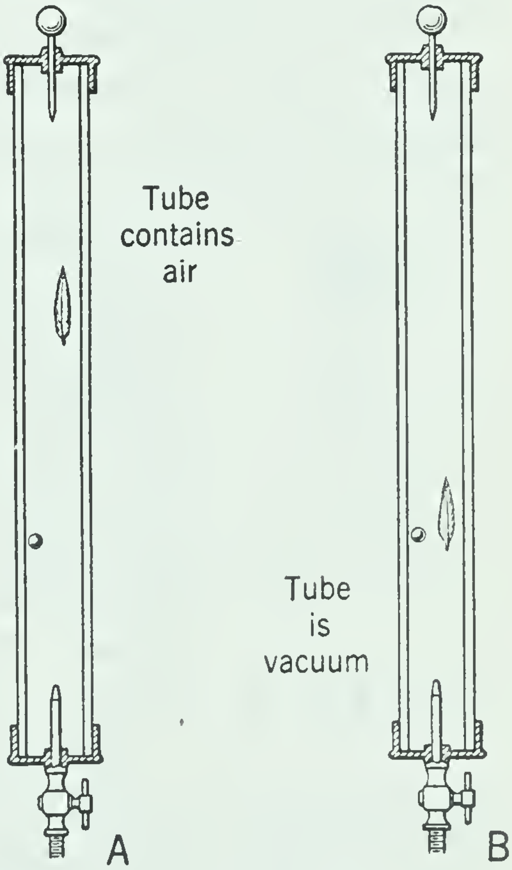


Fig. 7–19. Bodies fall at the same rate in a vacuum.

The laws of retardation and acceleration apply to bodies projected upward. An object thrown upward is uniformly retarded until it finally stops rising. Then as it falls it is uniformly accelerated. If we know the initial velocity with which it is projected upward, we may apply the laws of accelerated motion to find how high it will rise, and how long a time will be required for the ascent.

PROBLEM. An object is projected upward with a velocity of 100 m. per sec. How high will it rise? How long a time will be needed for the ascent? How long a time will elapse before it strikes the earth?

Solution. In the formula, $v = \sqrt{2gS}$, v and g are known; $g = 980$ cm. per sec., or 9.8 m. per sec. Substituting, $100 = \sqrt{2 \times 9.8 \times S}$, whence $S = 510.2$ m. From the formula, $v = gt$, we find the time required for the ascent, since v and g are known. Substituting, $100 = 9.8t$; whence $t = 10.2$ sec. Since it takes the same time for it to fall, it will be 20.4 sec. before it strikes the earth.

What is a pendulum? A body so suspended that it can swing to and fro about a horizontal axis is called a *pendulum.* The simple pendulum is defined as a particle so suspended by a *weightless cord.* Of course no such ideal pendulum can be constructed, but a ball suspended by a light thread is essentially a simple pendulum, Fig. 7–20. The point or axis about which a pendulum vibrates is called the *center of suspension.* As the ball or pendulum bob moves from A to B, it makes a *single vibration.* It makes a *complete vibration* as it moves from A to B and back again to A. The time required for a complete vibration is known as the *period* of the pendulum. The distance along the arc AC is known as the *amplitude* of vibration.

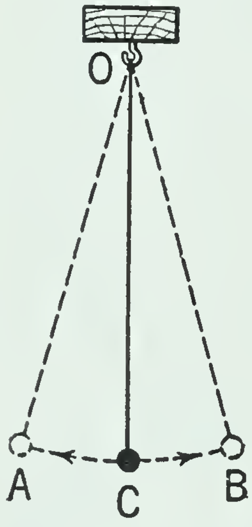


FIG. 7–20. The simple pendulum.

What are the laws of the pendulum? You may remember that it was Galileo who began the experiments on air pressure which were later finished by Torricelli. You have also read of his dropping objects of different density from the top of the leaning tower of Pisa. These simple experiments led to others from which Galileo developed the laws of accelerated motion and falling bodies. Now we see this philosopher as he sits in the cathedral in Pisa and watches a chandelier as it swings to and fro. With one finger on his pulse, he finds that successive vibrations are made in equal times. If this were not true, pendulums could not be used in clocks. Later he performed a series of experiments by means of which he learned several facts about the vibrations of the pendulum. These facts are known as the LAWS OF THE PENDULUM.

(1) *The time of vibration is independent of the weight or material of the pendulum.* This law is strictly true only if the pendulum vibrates in a vacuum. The air resistance has more effect upon a ball of cotton used as a pendulum bob than it does upon a ball of lead.

(2) *The time of vibration is independent of the amplitude, if the arc is small.* A pendulum usually swings through an arc of 10° or less.

(3) *The time of vibration is directly proportional to the square root of the length of the pendulum.* This law may be expressed algebraically as follows:

$$t : t' = \sqrt{l} : \sqrt{l'}$$

If we have two pendulums, one 25 cm. long and the other 100 cm., the longer one will vibrate just half as fast as the shorter one. The square roots of 25 and 100 are 5 and 10 respectively. Hence the times required for one vibration are in the ratio of 5 to 10, or 1 to 2.

(4) *The time of vibration is inversely proportional to the square root of the acceleration due to gravity.* A pendulum vibrates rather more rapidly at the North Pole than at the equator. If we use the letter l to denote the length of a pendulum, and g to denote the accleration due to gravity, then t, the time required for a single vibration, may be found by the following formula:

$$t = \pi\sqrt{\frac{l}{g}}$$

PROBLEM. Find the length of a pendulum that will make a single vibration in one second when g equals 980 cm. per second per second.

Solution. Substituting the values, $t = 1$, and $g = 980$ cm., in the formula (see Appendix C):

$$t = \pi\sqrt{\frac{l}{g}} \quad \text{or} \quad t^2 = \frac{\pi^2 l}{g}$$

$$1 = \frac{9.86965l}{980}, \quad \text{or} \quad 9.86965l = 980 \text{ cm.}$$

Whence $l = 99.29$ cm., the length of a pendulum that will make a single vibration in one second, where $g = 980$ cm. per sec. per sec.

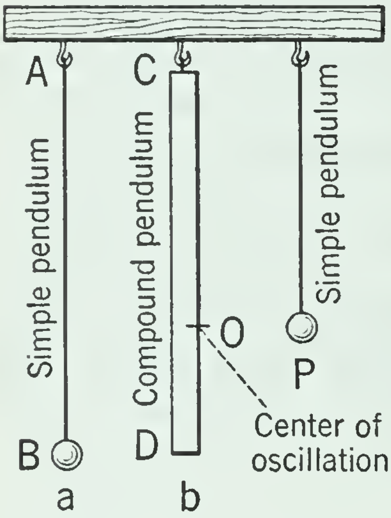


Fig. 7–21. The compound pendulum.

Where is the center of oscillation? The length of the pendulum shown in Figure 7–21*a* is measured from the point of suspension to the center of gravity of the ball *B*. A meter stick *CD* suspended from one end by a hook, although apparently of the same length as the pendulum *a*, does not vibrate at the same rate. It is a *compound* pendulum, Fig. 7–21*b*. Since its weight is distributed along its length, the several parts tend to vibrate as pendulums of different lengths. The particles near the lower end would, if isolated from the rest, vibrate more slowly. It is possible to find an intermediate particle, however, that would vibrate at the same rate as the undivided meter stick. This particle is at the *center of oscillation*. Experiment shows that the meter stick will vibrate at the same rate as the simple pendulum *P*, which is $\frac{2}{3}$ its length. If we bore a hole through the meter stick at the center of oscillation and suspend the meter stick from this point, it will have the same period as before. The real length of the meter stick swinging as a pendulum is the distance between the center of suspension and the center of oscillation.

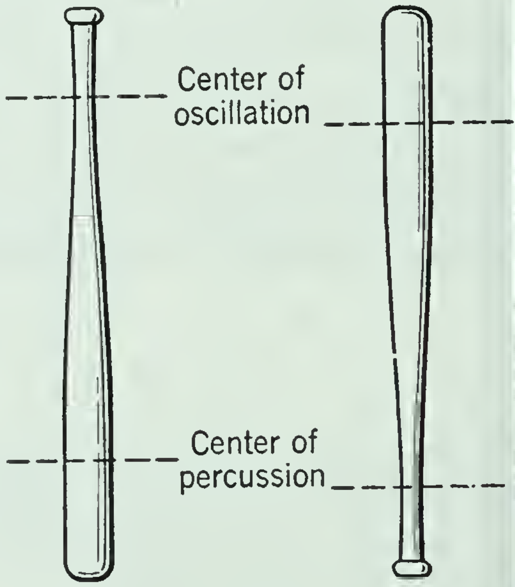


Fig. 7–22. The center of percussion.

Where is the center of percussion? If we strike the meter stick at its center of oscillation with a mallet when it is suspended as in Figure 7–21*b*, it will swing smoothly as a pendulum, without being jarred. If the meter stick is struck at any other point, it shivers or trembles instead of vibrating freely. The center of oscillation is coincident with the *center of percussion.* The center of percussion of a body is that point where a blow produces the least effect upon the center of suspension. A baseball player can drive a ball harder and farther if it strikes the bat at the center of percussion. If the ball strikes the bat at any other point, the bat "stings" the hands and is more likely to be broken. (See Fig. 7–22.)

Sometimes the handle of a hammer or ax is made too big for the weight of the head or blade. A woodsman, testing an ax that has too much wood in the handle, says that the ax is poorly hung. Its center of percussion is in the handle when it should be in the ax itself.

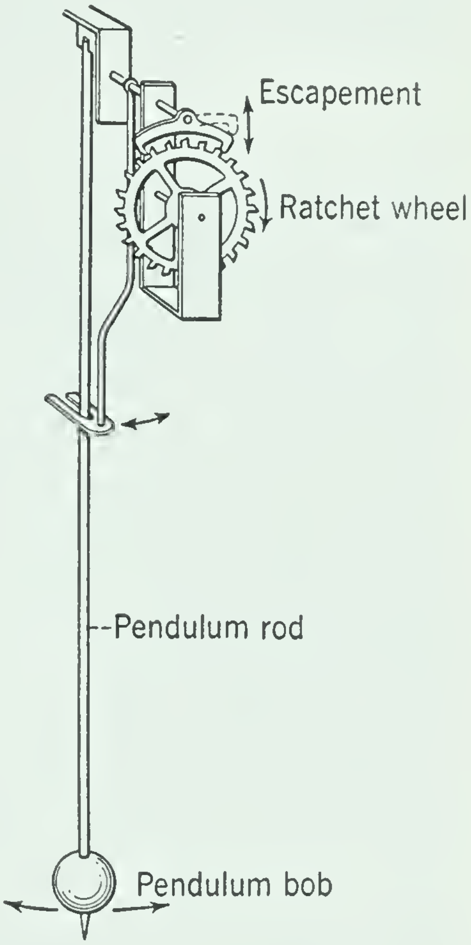


FIG. 7–23. The swinging of the pendulum releases the ratchet wheel.

What are some uses of the pendulum? The chief use of a pendulum is for keeping time. In a clock, the movement of the hands is controlled by the swinging of a pendulum. In Figure 7–23 the escapement wheel is one of a train of gear wheels that move the hands. Although these wheels are driven by a weight or spring, the escapement wheel is released one cog at a time by the vibrating pendulum, which thus indirectly controls the movement of the hands. A slight push from each cog as it escapes keeps the pendulum vibrating.

E. NEWTON'S LAWS OF MOTION

What are Newton's laws of motion? Sir Isaac Newton formulated three laws of motion that help to explain some very important principles of physics. While they are not capable of complete demonstration, yet observation and experiment give evidence that they are true as applied to the motion of both terrestrial and celestial bodies. We have already seen *how* bodies move; NEWTON'S LAWS explain *why* bodies move. They deal with the relation between force and motion.

1. INERTIA

Newton's first law. *Every body continues in its state of rest or uniform motion in a straight line unless it is compelled by some external force to change that state.* This law is really a statement of the property of inertia, which was discussed in Chapter I. No inanimate body can move or stop moving. A horse must pull very much harder to start a heavy load than to keep it moving; when started, however, it continues to move for a time unless a backward force is applied to stop it. That an object tends to continue in motion in a *straight* line is clearly shown by the fact that mud flies from a rapidly rotating carriage wheel, or water from a grindstone along a line tangent to the circumference. If ice offered no resistance by friction, one who starts to slide on a lake of ice would continue to slide in a straight line entirely across the lake. Automobile drivers in rolling country sometimes coast down one hill and the inertia of the moving car will carry it part way up the next hill. The practice, however, is dangerous.

What is momentum? The student may place one hand flat on the table and lay a 1-lb. weight upon it. The effect is not unpleasant, but he may not care to continue the experiment by lifting the weight to a height of a foot or more and dropping it upon his hand. The impact in the second case is due to the *momentum* of the weight, or the product of its mass times its velocity. A ferryboat in docking moves very slowly, but a foot caught between the slowly moving boat and the dock would be crushed by the momentum of the boat. *This momentum is equal to the mass of the boat times its velocity.* A rifle bullet has terrific impact because its velocity is from 1500 to 3000 ft. per sec., and its small weight of a few ounces multipled by such a high velocity gives a large momentum. A mass of 1 gm. moving with a velocity of 1 cm. per sec. has one unit of momentum (C.G.S.). A mass of 1 lb. moving with a velocity of 1 ft. per sec. has one unit of momentum (F.P.S.). A 2000-ton boat moving with a velocity of 20 ft. per sec. has a momentum of 80,000,000 units.

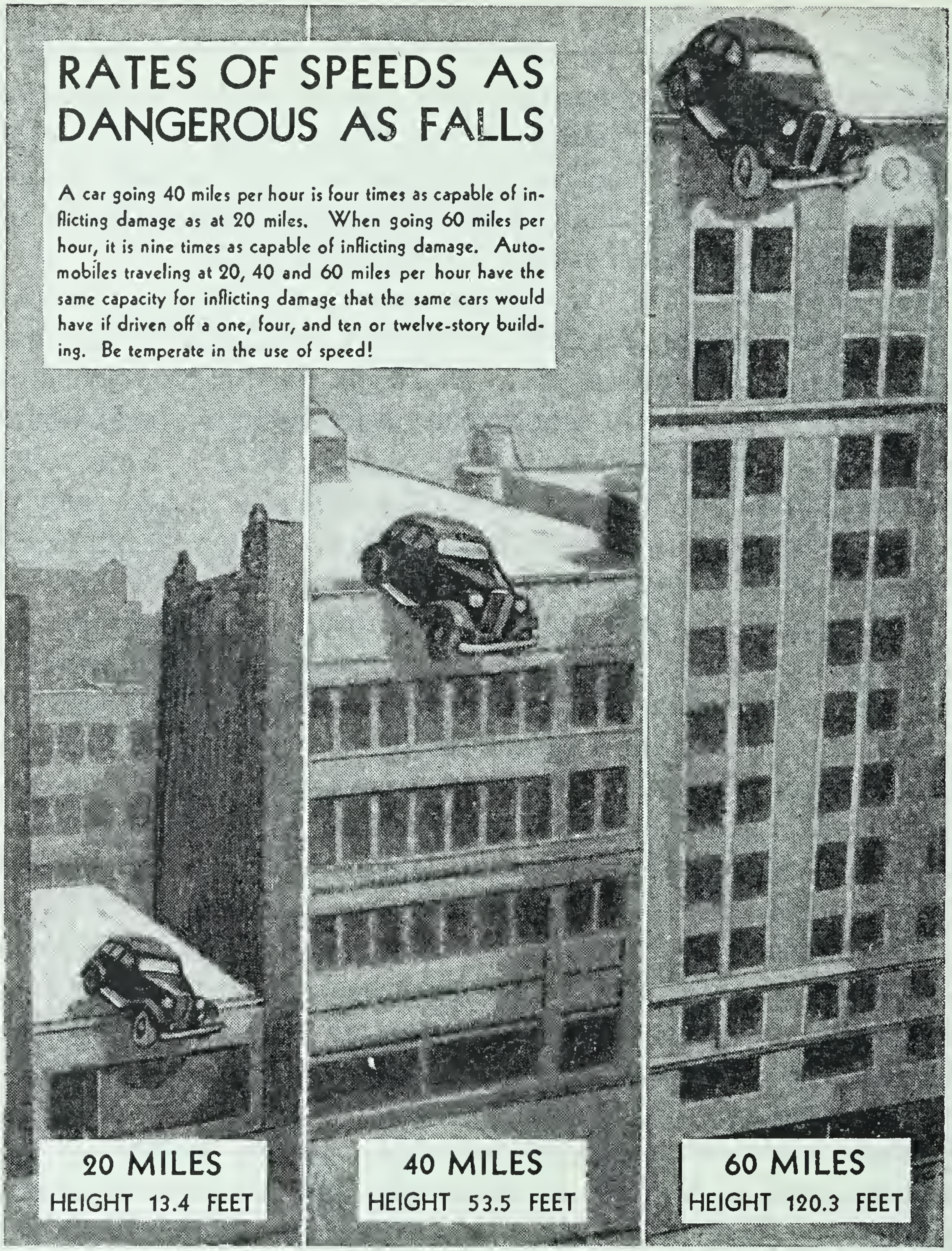
How hard do we hit? If we are walking only 4 ft. per sec. and collide with the edge of a door, we get a terrific jolt. A car running 20 mi. per hr. hits a tree. At 20 mi. per hr. its velocity is 29.3 ft. per sec. To gain that velocity a freely falling body would need to drop a trifle more than 13 feet. ($v = \sqrt{2gS}$.) You would get the same jolt by driving a car off a roof 13+ ft. high, as you would by driving into a fixed object at 20 mi. per hr. Figure 7–24 shows the effect of increased speeds upon impact.

It is possible to increase the momentum of a body by increasing its velocity. A larger force, acting upon a body for a short time, is needed to bring it up to a certain velocity than a smaller force acting for a longer time. The player who "follows through" on his golf or tennis stroke imparts greater velocity to the ball. A baseball player is more likely to knock a home run when he "follows through" than when he merely lets his bat "meet" the ball.

The momentum of a revolving wheel depends upon the revolutions per minute, the weight of the wheel, and the diameter of the wheel. An increase in revolutions per minute means an increase in speed, which, as you have already seen, increases momentum. Assuming the number of revolutions per minute to be constant, an increase in diameter could cause an increase in momentum, and an increase in the weight of the wheel would also increase the momentum. It is the momentum of flywheels which enables them to keep machines moving through intervals during which no effort is applied, and to insure smoother operation of machinery.

2. ACCELERATION

Newton's second law. Newton's first law states what happens to matter when forces *do not act* upon it; his second law is a state-



RATES OF SPEEDS AS DANGEROUS AS FALLS

A car going 40 miles per hour is four times as capable of inflicting damage as at 20 miles. When going 60 miles per hour, it is nine times as capable of inflicting damage. Automobiles traveling at 20, 40 and 60 miles per hour have the same capacity for inflicting damage that the same cars would have if driven off a one, four, and ten or twelve-story building. Be temperate in the use of speed!

Courtesy of the Travelers Insurance Company

Fig. 7–24. At 40 miles per hour a car hits 4 times as hard as it does at 20 miles per hour. At 60 miles per hour the force of impact is 9 times as great. If two cars, each traveling 20 miles per hour, happen to meet head-on, the force of impact is the same as that which occurs when one car traveling 40 miles per hour hits a tree or a wall. What do you think your chance of survival would be if the car in which you were riding at 40 miles per hour should collide head-on with an oncoming car traveling 40 miles per hour?

ment of what does happen when forces *do act* upon it. If a force of 1 lb. acting upon a body produces a certain acceleration, a force of 2 lb. will produce double the acceleration. The second law may be stated as follows: *Rate of change of momentum is directly proportional to the acting force, and takes place in the direction in which the force acts.* Experience teaches us that motion takes place in the direction of the force which produces it. If a ball thrown with a given force moves with a velocity of 50 ft. per sec., the force must be doubled to make the ball move with a velocity of 100 ft. per sec.

When two or more forces act together, each produces its own change of momentum, independently of the other forces. Thus the force that drives a bullet in a horizontal direction acts continuously; at the same time, the force of gravity is gradually pulling the bullet toward the earth. A ball dropped from the top of a tall tower strikes the ground at the same instant as a bullet fired horizontally from the top of the tower, although the latter may fall several thousand feet distant. (See Fig. 7–25.)

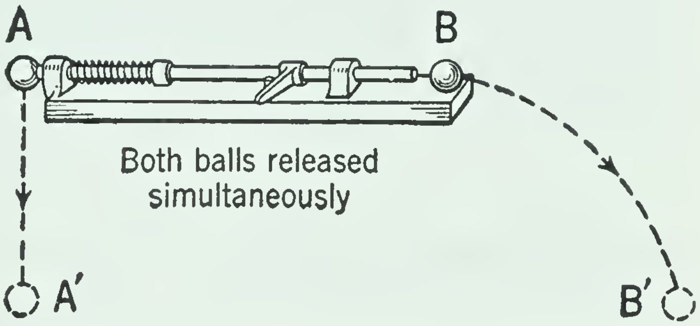


FIG. 7–25. Both balls strike the floor at the same instant.

DEMONSTRATION. How can we prove the statement just made concerning the ball and the bullet? When the trigger is released on an apparatus like that shown in Figure 7–25 the spring causes the plunger to knock ball *B* to the right and at the same instant drops ball *A*. Support the apparatus in a level position about three feet above the top of the demonstration table. Release the trigger and listen carefully to see if you hear two impacts when the balls strike the table or only one. Result?

If a force of 1 lb. acting upon a body produces an acceleration of 1 ft. per sec. per sec., then a force of 2 lb. acting upon the same body would impart to it an acceleration of 2 ft. per sec. per sec. *The acceleration is directly proportional to the acting force.* By using the letters f and f' to represent the two forces, and the letters

a and a' to represent the respective accelerations, then we may express the above statement in a mathematical formula as follows:

$$f : f' = a : a'$$

In the case of a freely falling body, one of the forces is known, because it is equal to the weight W of the body. The acceleration g is also known, because it is equal to the acceleration due to gravity. Then the formula becomes:

$$f : W = a : g$$

By the use of this formula one can calculate the force needed to impart to a body of known weight any desired acceleration.

PROBLEM. A car weighs 3000 lb. What force is needed to impart to it an acceleration of 10 ft. per sec. per sec.?

Solution. By substitution, we get,

$$f : 3000 = 10 : 32$$
$$f = 937.5 \text{ lb.}$$

The path of a projectile is curved. (1) *Fired horizontally.* Many persons have the idea that a rifle bullet fired horizontally travels in a straight line, but it doesn't. Gravity acts upon it immediately and constantly, pulling it from its course. Suppose its velocity is 3000 ft. per sec.; at the end of the first second, air resistance being ignored, it will have traveled 3000 ft.; but in 1 second a body falls 16.08 ft., and the bullet would strike 16.08 ft. below the point at which it was aimed. In 2 seconds the bullet travels 6000 ft., but it drops in the same interval 64.32 ft. (See Fig. 7–26*A*.) Of course, the

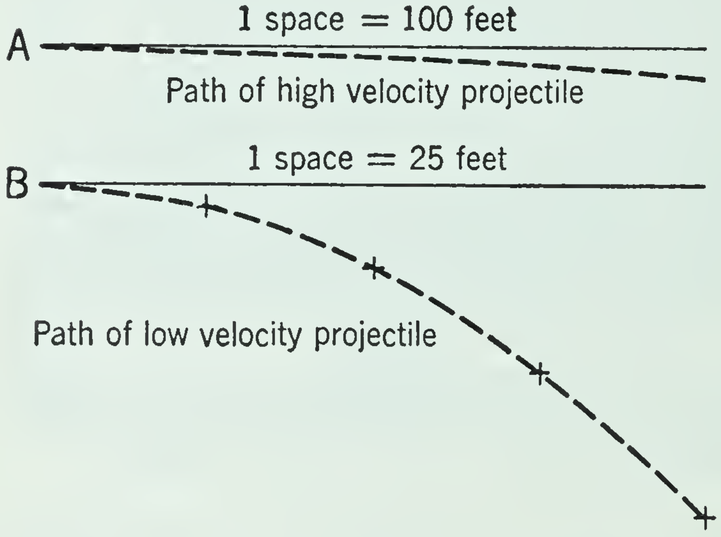
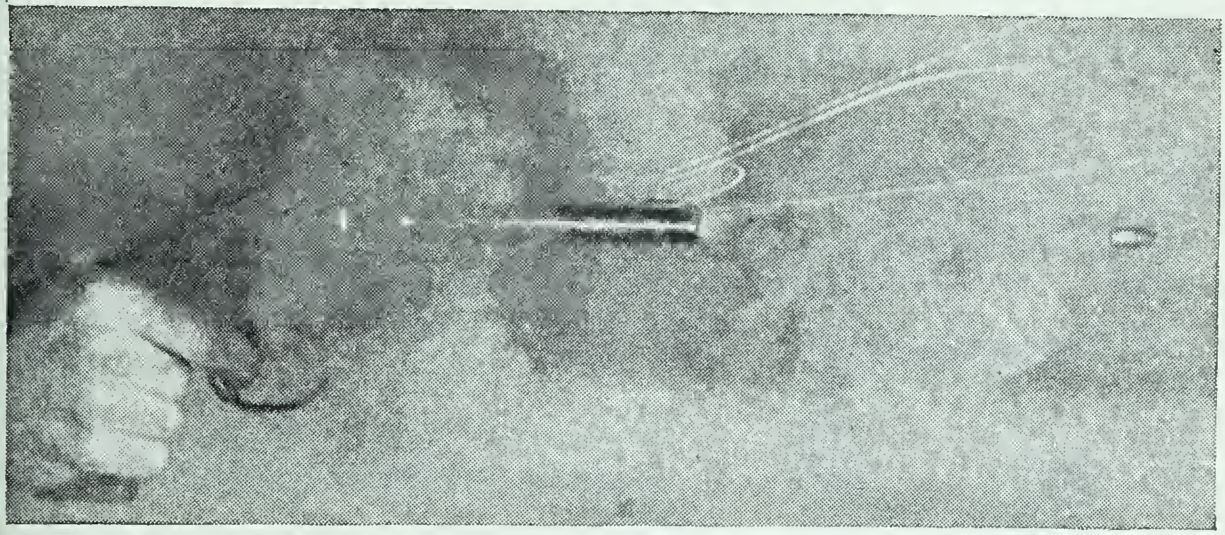

1 space = 100 feet
A
Path of high velocity projectile
1 space = 25 feet
B
Path of low velocity projectile

FIG. 7–26. *A*. Curve of a high velocity projectile. *B*. Curve of a low velocity projectile.



Courtesy of the Remington Arms Company, Inc.

FIG. 7–27. A pistol bullet photographed at the instant it left the pistol.

greater the velocity, the more nearly the curve approaches a straight line. The curve of Fig. 7–26*B* shows the path of a ball thrown with a horizontal velocity of 100 ft. per second. (See also Fig. 7–27.)

(2) *Fired at an angle.* In the use of the modern rifle, in which the bullet may have a velocity of 3000 ft. per second, the path of the bullet is so nearly horizontal that no correction need be made for *short* distances. When the object is more remote, the rear sight of the rifle is raised a trifle. When the rifle is then aimed at an object, the end of the barrel is raised slightly. The farther away the object, the more the rear sight must be elevated before aiming. The muzzle of a field gun is always elevated so that the projectile is fired at an angle. Figure 7–28 shows the path such a projectile may take. The angle *BAC* is the *angle of elevation.* *AC* and *AD* are the component horizontal and vertical velocities, and *AR* is the *range.* The path *ABR* is called the *trajectory.* The higher the velocity of the projectile, the flatter the trajectory. (See Fig. 7–26.) Under actual conditions, air resistance reduces the range, and corrections must be made for windage (deflection due to wind).

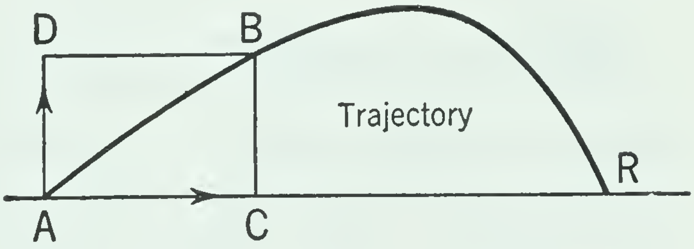


FIG. 7–28. Path of a projectile that is fired from an angle.

We can find the composition of velocities. From these facts we can see that we may have composition of velocities as well as composition of forces. Since it requires force to produce velocity, and we know that forces can be represented graphically, it seems reasonable to believe that velocities can be plotted in the same manner. In fact not only can we plot velocities, but we can also determine the resultant of two or more velocities acting together. If a man rows a boat across a stream at a velocity of 4 miles per hour, and the current carries the boat downstream with a velocity of 4 miles per hour, we can find the *resultant* velocity by drawing the parallelogram shown in Fig. 7–29, and calculating the length of the diagonal. If the stream were 4 miles wide, the man would row across in an hour, but he would land 4 miles downstream, unless he kept the bow pointed somewhat upstream. He would actually have traveled along the diagonal of the parallelogram a distance of 5.66 miles:

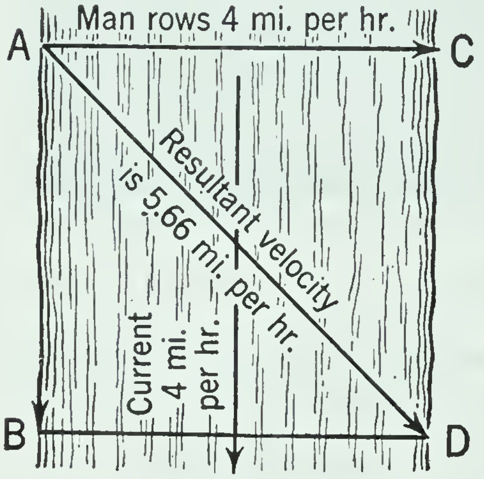


Fig. 7–29. Velocities are compounded just as we compound forces.

$$(\sqrt{(4)^2 + (4)^2} = 5.66)$$

Effect of air resistance. It was pointed out in our discussion of freely falling bodies and of the path of a projectile that air resistance was disregarded. In all practical applications such as artillery and bombing by airplanes, allowance must be made for air resistance. The effect of this resistance depends upon the shape and density of the projectile and the density of the air through which it travels. (See Figs. 7–19*A* and 7–19*B*.) Experiments with freely falling objects simulating human bodies in shape and density have shown that they cease to be accelerated by the force of gravity after they have fallen about 1800 feet. At this point the retarding force of the air resistance is equal to the force of acceleration due to gravity; therefore the speed becomes uniform. This speed for the dummies tested was about 160 feet per second or a velocity one-half that which they would have had at the end of an 1800 foot fall in a vacuum.

DEMONSTRATION. A bomber flying horizontally at the rate of 300 miles per hour (440 ft. per sec.) releases a bomb at an altitude of 6400 ft. Plot the trajectory of the bomb, using the vertical axis of the graph for the motion in feet and the horizontal axis representing the curve or path of the projectile. Draw a solid curve representing the estimated path of the bomb, taking into account air resistance.

3. ACTION AND REACTION

Newton's third law. A man rows a boat toward the shore of a lake. When he is 3 or 4 feet from shore, he steps on the bow and attempts to leap ashore. The force with which he impels himself forward reacts and pushes the boat backward. The man misses his mark and falls into the water. If you wish to jump forward you must stand on something fixed which resists this acting force. The end of a garden hose lying on the lawn is pushed backward by the reaction of the water as it issues from the nozzle. Water reacts against the oars of a boat and the arms of a swimmer; its reaction against the propellers makes the movement of a steamboat possible. The reaction of the air against the wings of a bird enables it to fly. The air reacts against the propellers of an airplane as they pull the plane forward, and the reaction against the plane is resolved into two components, one of which lifts the plane. (See Fig. 6–39.)

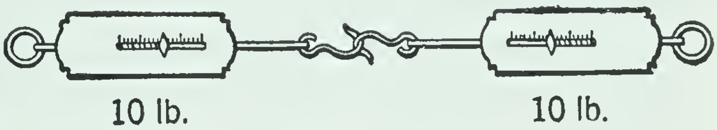


FIG. 7–30. Action equals reaction.

If we fasten one spring balance to the table, hook another spring balance to it as shown in Figure 7–30, and pull steadily, it may be shown that the *reaction is equal to the action.* Both balances show the same reading. The collision balls of Figure 7–31, may also be used to show that the force of reaction is *equal* to the action. If one ball is raised and let fall, one ball flies out at the opposite end of the line. When two balls are let fall, two balls at the other end

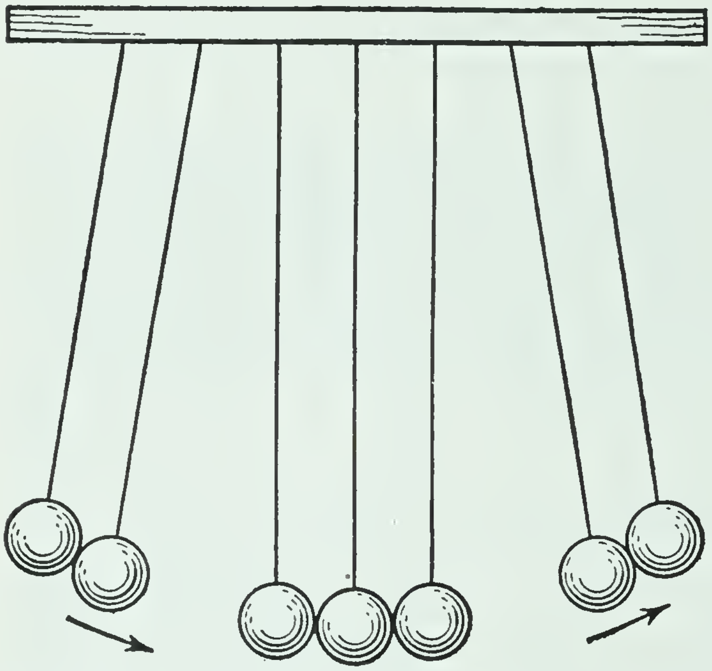


Fig. 7–31. Further proof that reaction equals action.

of the line move in response to their action. Newton's third law is usually stated as follows: *To every action there is an equal and opposite reaction.*

Some have tried to argue that no motion can occur, if action and reaction are equal. But in reaction *two different* bodies are always involved. The water reacts against the oars, and the air against the propeller. If two boys pull upon a light wagon in opposite directions, the wagon moves in the direction of the greater force. Here *two forces* act upon *one body.* This is an example of *counteraction,* in which there is an *unbalanced* force. *Reaction* is shown by the fact that the earth reacts against the feet of each boy with a force which is exactly equal to the pull he exerts. The driving wheels of a moving automobile push backward on the ground, but the ground pushes forward on the wheels. This is reaction, but when this car tows another car the pull on the towline is an unbalanced force.

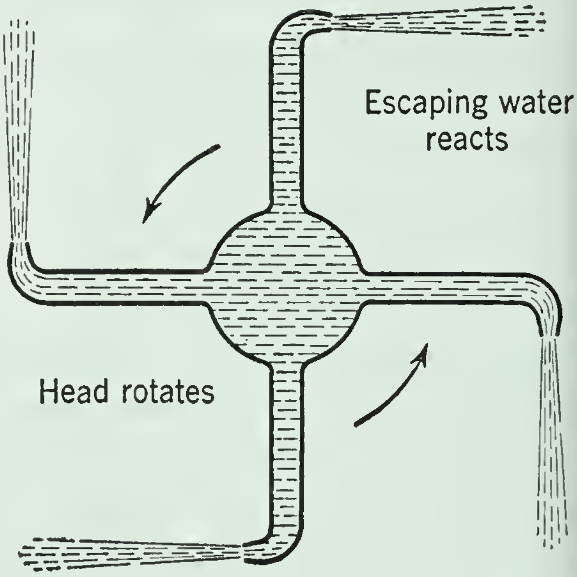


Fig. 7–32. Water escaping from nozzles reacts in a backward direction against them, thus producing rotation.

What are some applications of reaction? We have already seen that reaction makes flying, swimming, and rowing possible. The *rotary* lawn sprinkler works on the same principle. (See Fig. 7–32.) As the water issues from the nozzles, the rotating head is turned backward, thus scattering the water in all directions. The pinwheel as used in fireworks is turned in the same manner. The "kick" or recoil of a gun is an example of reaction. The recoil is sometimes used to eject the empty cartridges in rapid-fire guns. In the *disappearing* guns used for coast defense, the recoil of the gun carries the gun back on its carriage and down behind the fortifications. (See Fig. 7–33.) Ordinary walking is possible because the earth pushes forward against us as hard as we push backward.

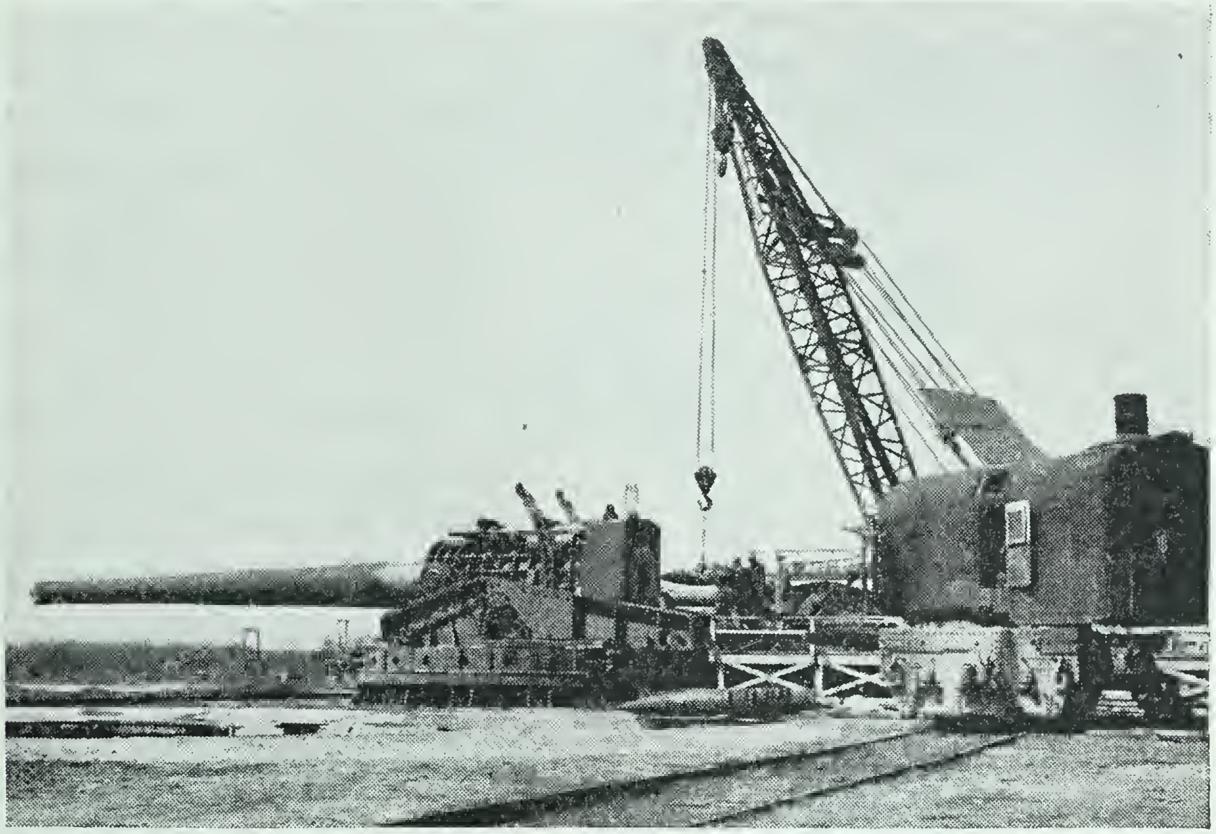


Photo by U.S. Army Signal Corps

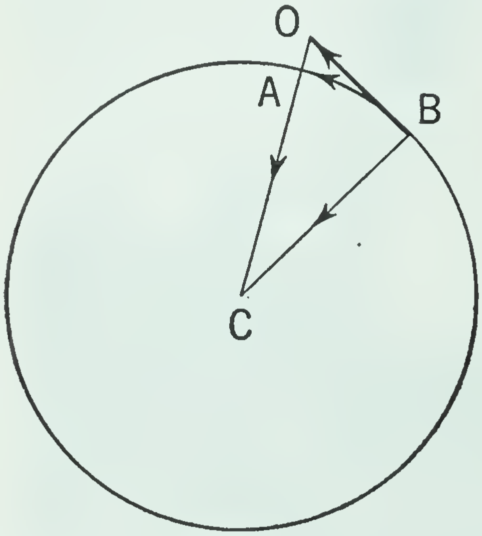
FIG. 7–33. U. S. Army 16-inch seacoast rifle which fires a 1-ton projectile a distance of 30 miles.

The friction between the tires of an automobile and the road must be greater than the reaction to the driving force of the motor transmitted to the wheels. You have probably noticed that when a car is standing with its motor running, accelerating or racing of the motor makes the body of the car tend to revolve slightly to one side. This is evidence of the reaction of the body of the car to the force of acceleration on the revolving motor.

Demonstration. How can we illustrate reaction? Place an electric fan on a Hall's car or any kind of small wagon (a toy wagon will do). Connect the fan to a current outlet and turn it on. Observe the effect of the air current on the position of the car or wagon. Explain.

F. CURVILINEAR MOTION

How is curvilinear motion produced? From Newton's first law we learned that a body which has acquired velocity continues to move in a straight line. If a second force acts upon the moving body at right angles to its path, it will be deflected from its rectilinear line, and its motion will become curvilinear. To illustrate, we may tie one end of a string to a ball. Holding the other end firmly, we may swing the ball in a circle about the hand as a center. The pull of the hand upon the cord deflects the ball away from its rectilinear path and toward the center. (See Fig. 7–34.) As the ball moves along the circumference from *B* to *A*, the pull toward the center has deflected it a distance equal to *AO*. The constant pull that deflects a body from its rectilinear path and compels it to move along a curve, is called *centripetal* (center-seeking) force.



Ball B tries to follow path BO. String pulls it toward center

Fig. 7–34. The ball tends to break the string and follow the path *BO*.

1. CENTRIFUGAL FORCE

It "flees the center." If the revolving body of Figure 7–34 did not have inertia, it would be pulled to the center. If the earth in revolving around the sun did not have inertia, it would fall into the sun. The reaction due to the inertia of the moving ball offers resistance to the centripetal pull and tends to break the string. If the string breaks, the ball immediately begins to move in a straight line along a tangent to the curved path. *The resistance that a moving body offers to deflection from a straight line is commonly known as centrifugal force.* Some physicists object to the use of the term "force" as applied to the tendency a body offers to resist being deflected from its path, but beginners find it easier to think of such reaction as *centrifugal force.*

Some illustrations of centrifugal force. Mud flies from a rotating carriage wheel when the centrifugal force exceeds its adhesion to the tire. Water flies off at a tangent from a rapidly turning grindstone. David knew that a high velocity could be imparted to a missile by putting it in a sling and whirling it around his head. That knowledge and his skill in controlling the direction of the stone which he picked out of the brook made him the conqueror of Goliath. Emery wheels sometimes burst when driven at high velocity; the centrifugal force exceeds cohesion. An automobile rounding a curve at high speed is likely to go off the road. (See Fig. 7–35.)

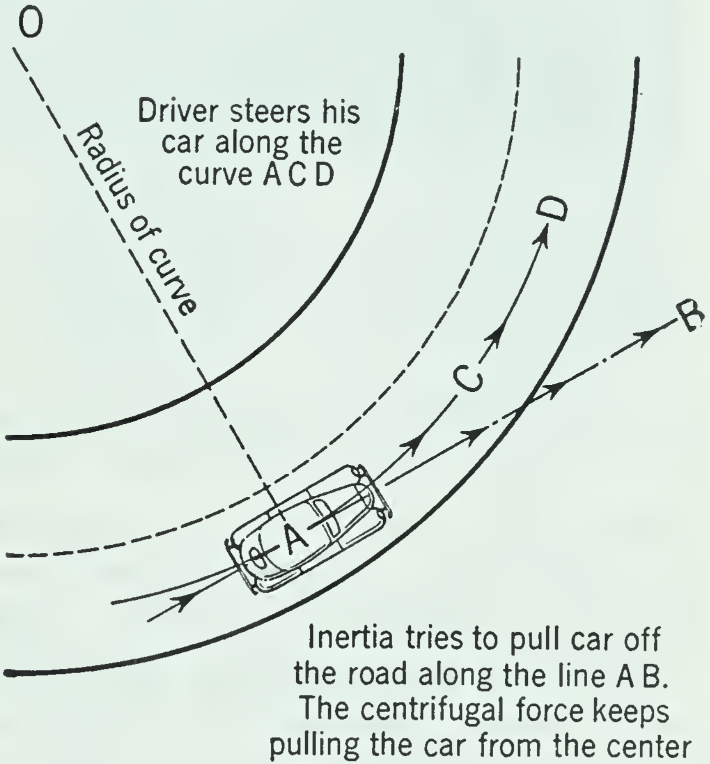
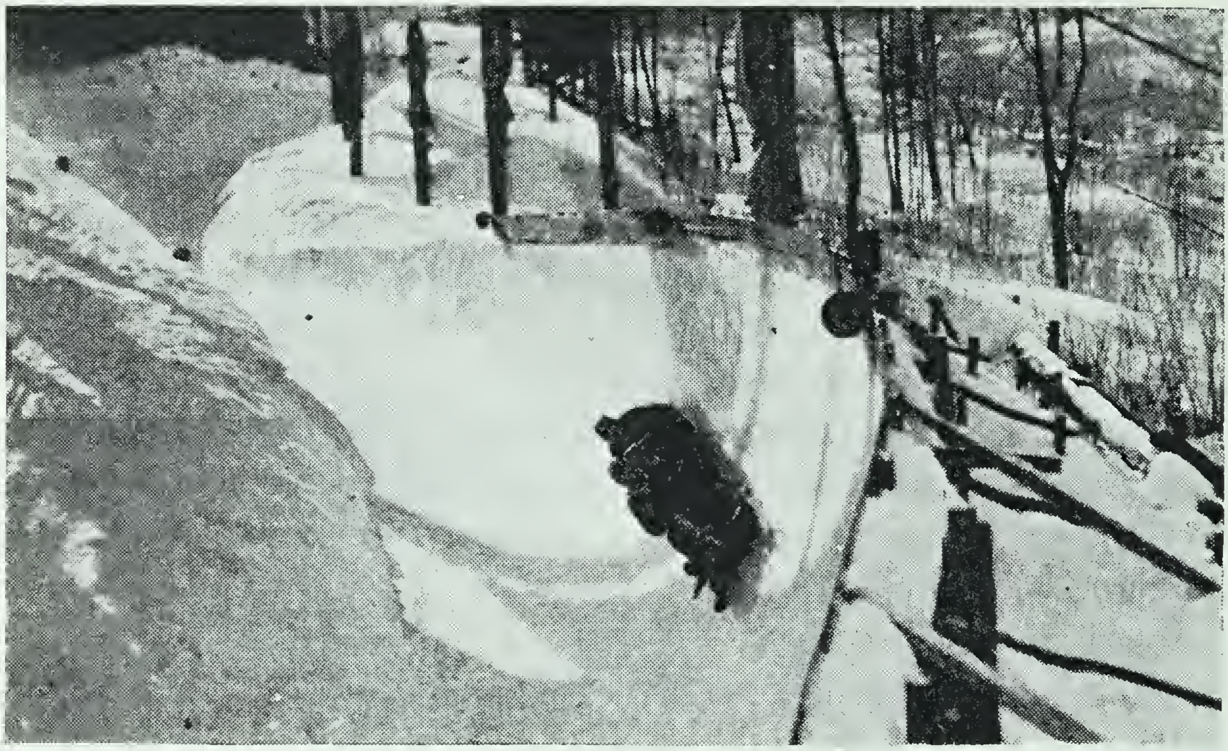

O
Radius of curve
Driver steers his car along the curve A C D
D
C
B
A
Inertia tries to pull car off the road along the line A B. The centrifugal force keeps pulling the car from the center of the curve, which is at point O.

Fig. 7–35. The centrifugal force is attempting to pull the car off the road.

How do you counteract the effects of centrifugal force? You lean toward the center when you are skating around a curve. To prevent the overturning of a train rounding a curve, the tracks are so banked that the rail on the outside of the curve is higher than the inside rail. Running tracks in gymnasiums and race tracks of all kinds are banked at curves to help nullify the effects



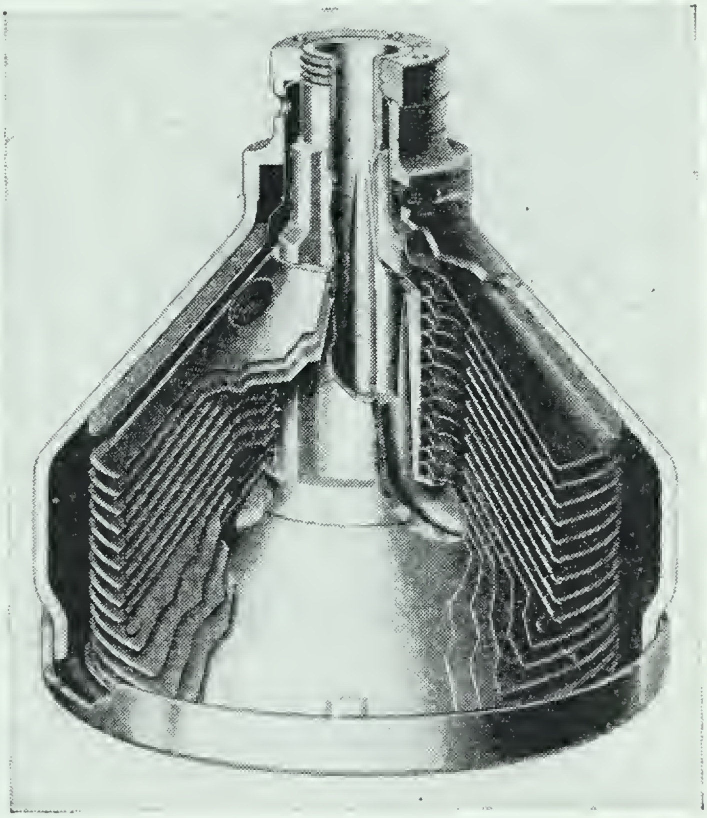
Keystone View Company

Fig. 7–36. The bob-sled track is banked at the turns to help counteract centrifugal force. This picture taken at Lake Placid shows a sled almost perpendicular against a banked turn.

of centrifugal force. Most of our new highways are banked at curves to help prevent accidents. Since centrifugal force depends upon inertia, and inertia is a general property of all matter, we cannot do away with centrifugal force, but we can often prevent damage by nullifying its effects. (See Fig. 7–36.)

What are some practical applications of centrifugal force? In former years, farmers let the milk stand until the lighter cream rose to the top of the pan or crock. Then the cream was skimmed off the top of the milk. Now centrifugals are used to separate the cream from the milk. The milk enters the top of the separator, and is thrown against the surfaces of several funnel-shaped discs or blades that rotate at a high speed. The cream, which is lighter than the milk, rises along the top surfaces of the blades and issues from an opening near the center. (See Figs. 7–37 and 7–38.) The skim milk passes to the outside of the rotating blades, where it is drawn off through a separate outlet.

Several passenger cars are equipped with a variation of the ordinary plate clutch known as the semicentrifugal clutch. On the outer ends of the pressure levers of this type of clutch are weights. Each pressure lever has its pivot between the clutch release, and the pressure-lever needle bearing therefore acts as a first-class lever. As the speed of the motor increases, the centrifugal force of the weight produces a counterclockwise movement, thereby causing the needle bearing of the pressure lever to force the driving plate against the driven plate. This pressure, therefore, is in addition to the pressure produced by the clutch springs. This type of clutch decreases the amount of foot pressure necessary to operate the clutch pedal, since it permits the use of less spring pressure.



Courtesy of the de Laval Separator Company

FIG. 7–37. The whole milk enters at the top and is separated by centrifugal force. The blades, or discs, rotate at a speed of from 6000 to 8000 revolutions per minute. The skim milk, which is denser, is thrown against the lower surfaces of the discs, whence it passes down to the outer edge of the bowl. The cream, which is less dense than the milk, passes upward and inward toward the center.

James Watt devised a *governor* to regulate the speed of a stationary engine. It is operated by a belt driven from the shaft of the flywheel of the engine. As the speed increases, the two balls move farther apart, since centrifugal force increases with the speed. (See Fig. 7–39.) As they move outward, they lift one end of a lever which shuts off some of the steam. The reverse occurs when the engine begins to slow down.

Some automobile *speedometers* are operated on a similar principle. Small weights are hinged to a shaft which is driven through

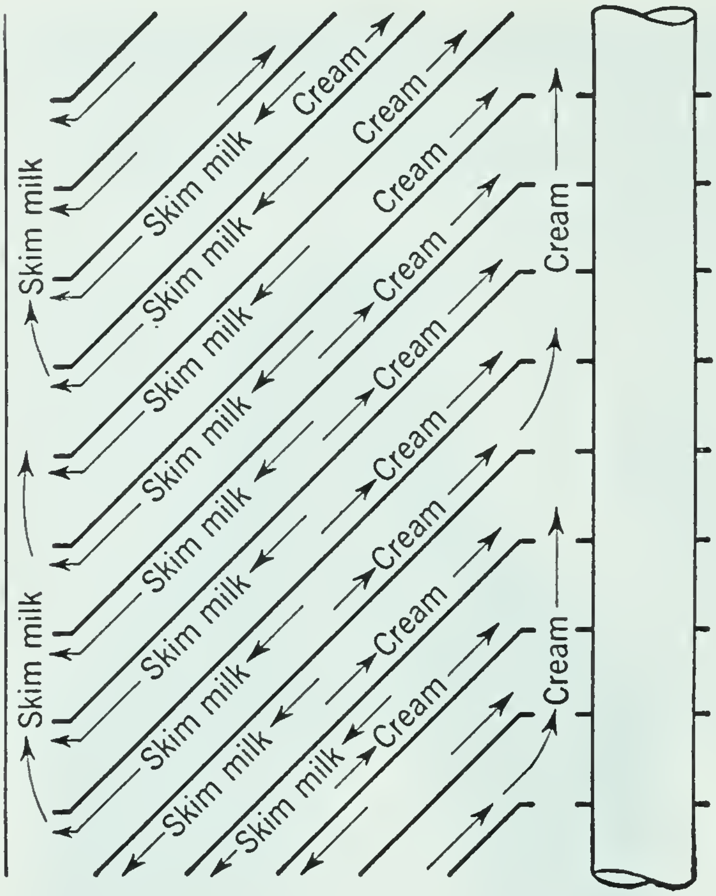


Fig. 7–38. The blades of the cream separator.

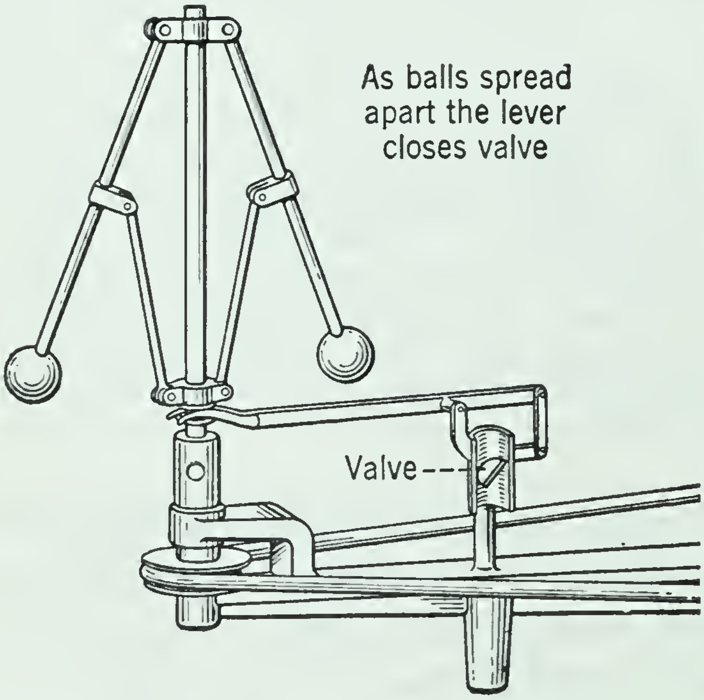


Fig. 7–39. Centrifugal force controls the governor and regulates the engine speed.

a flexible cable by means of a gear attached to the drive shaft or to one of the wheels. As the speed increases these weights pull outward and move the pointer over a graduated dial.

Wet solids may be partially dried by putting them in a perforated cylinder, which is then rapidly rotated. The water is thrown out through the openings. Crystals are dried in this manner; laundries use this method for drying clothes. (See Fig. 7–40.) Some types of home electric washing machines use the centrifuge for drying clothes.

A very efficient type of water pump depends for its action upon centrifugal force. (See Fig. 7–41.) As the rotor turns rapidly in the direction shown by the outer arrows, the water is forced by the rotating blades out through the discharge pipe.

Liquids that contain sediment are often centrifuged instead of being filtered. The sediment is removed from varnish by this method. In making rayon, a solution of cotton must be passed through openings .005 mm. in diameter. As the solution of cotton flows into a solution of sodium hydroxide, a fiber is formed. It takes 20 of the small fibers thus produced to make a single thread of the rayon. Since these openings are so minute, the solution is centrifuged at 8000 or 10,000 revolutions per minute before spinning, in order to remove any sediment that might clog the openings. (See Fig. 7–42.)

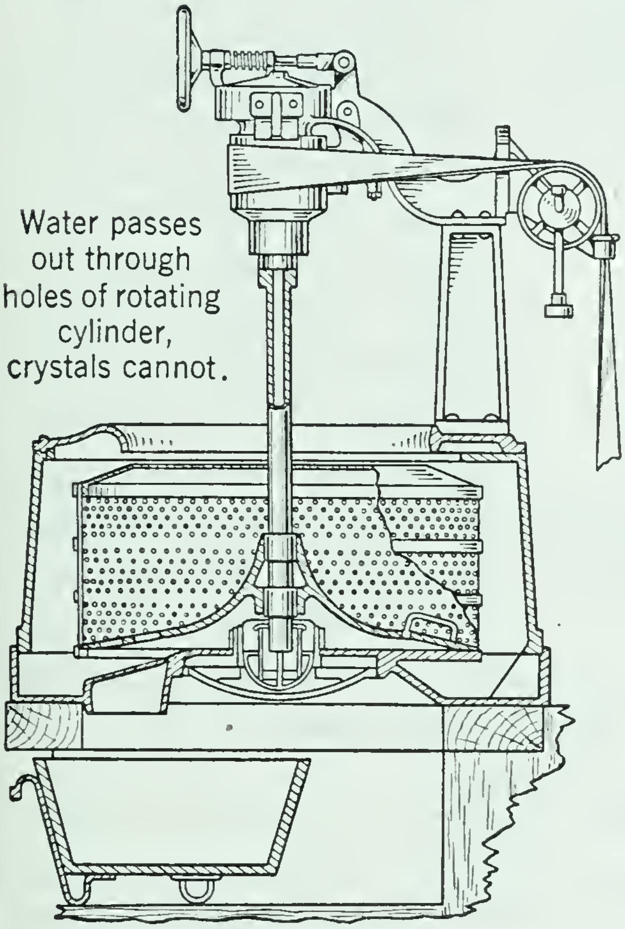

Water passes out through holes of rotating cylinder, crystals cannot.

FIG. 7–40. Centrifugals are used to dry clothes, crystals, and various chemicals.

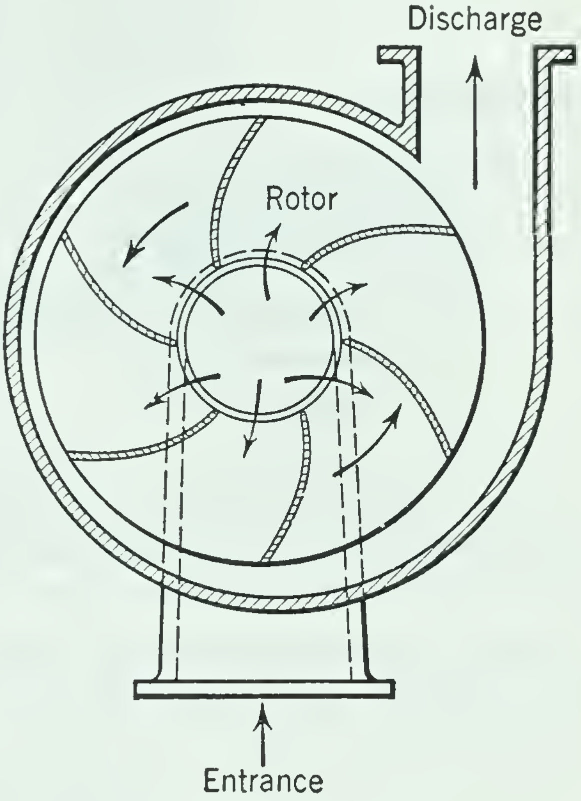


FIG. 7–41. The centrifugal pump is very efficient. Small ones are used to keep the water circulating through the cooling system of an automobile.

Even our amusement parks utilize centrifugal force. At Coney Island the "human pool table" is an example. The "whip" and the "loop-the-loop" are other examples.

How we calculate the magnitude of centrifugal force. It is possible to measure the pull which the ball of Figure 7–34 exerts upon the string. If we use a ball which has just double the mass, the pull on the string will be just twice as great. Hence we conclude that *the centrifugal force is directly proportional to the mass.* If we shorten the string, the ball is pulled from its path faster and it reacts with greater force to break the string. Careful measurements show that *centrifugal force is inversely proportional to the radius of curvature.* As we swing the ball faster, so that the velocity along the curve increases, it pulls more strongly on the cord. Accurate measurements show that the *centrifugal force is directly proportional to the square of the velocity.* If v = velocity in centimeters per second, m the mass in grams, and r the radius in centimeters, then the following formula can be used:

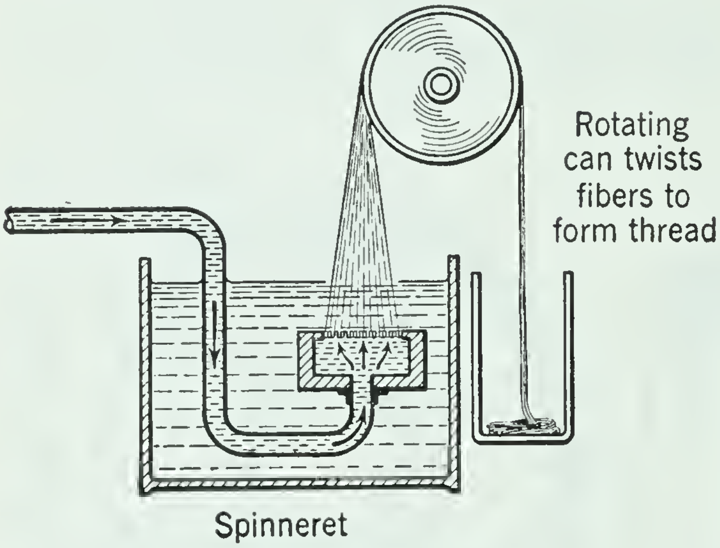


FIG. 7–42. As the solution of cotton flows from the tube at the left into the caustic solution through the tiny openings, it suddenly hardens into fine threads or filaments.

$$CF \text{ (in gm.)} = \frac{mv^2}{gr}$$

In the English system, if mass is in pounds, radius in feet, and velocity in feet per second, then:

$$CF \text{ (in pounds)} = \frac{mv^2}{gr}$$

PROBLEM. A ball that weighs 10 lb. is being rotated by means of a cord 4 ft. long. If its velocity is 20 ft. per second, find the force in pounds that tends to break the cord.

Solution. v, g, r, and m are known. Substituting the values in the formula:

$$CF = \frac{mv^2}{gr}, \text{ we get, } CF = \frac{10 \times (20)^2}{32 \times 4}$$

$$CF = 31.25 \text{ lb.}$$

DEMONSTRATIONS. What force does a weight exert when swung in a circle on the end of a string? (1) Instead of swinging a ball in a circle about the hand as a center, as in Figure 7–34, swing a 500-gm. weight by turning around, thus using the body as the center of the circle. Let the string *CB* be about 4 ft. in length. Attach the string to a spring balance and hold the balance so that the force necessary to pull the weight in a circular path is exerted upon the spring of the balance. While swinging the weight in a circle around the body note the balance reading. How does this reading compare with the 500-gm. weight? Explain.

(2) Rotate a glass globe containing colored water and mercury. (See Fig. 7–43.) Observe the positions of the two liquids.

(3) Examine the governor of a phonograph mechanism.

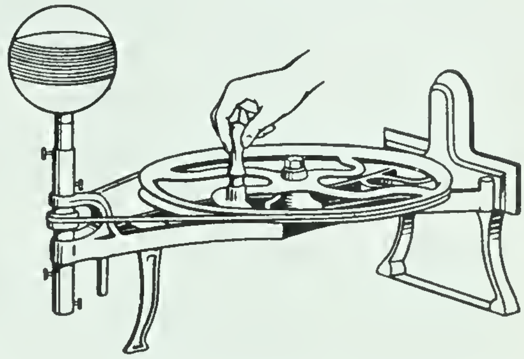


Fig. 7–43. Rotator illustrating centrifugal forces.

Automatic spark advance. When a gasoline engine is operating at high speeds it is necessary to have the spark occur in the cylinder earlier than when running at low speeds. This necessary *spark advance* runs from the beginning of the power stroke back to the end of the compression stroke. An attempt to start the motor with the spark advanced in timing to the end of the compression stroke would result in a kickback. As a safeguard against this, many automobile and airplane engines are equipped with an automatic spark advance. Some of these operate on the centrifugal principle. Small weights are hinged to a shaft, similar to that in Figure 7–39, which is geared to the timing gear. As the speed of the motor increases, these weights pull outward and move the lever which advances the spark.

What is the principle of the gyroscope? You may be familiar with the toy gyroscope and the spinning top. The centrifugal force of a heavy rotating wheel gives it great stability. When such a wheel is rotating rapidly in a certain plane, considerable force must be used to change the plane of rotation. The principle of the gyroscope has been put to practical use in many ways. The Sperry type of stabilizer used on airplanes depends upon this principle. A gyroscopic compass is now used on all submarines and on many airplanes. The flywheels on the engines of a steamship are mounted on axes that extend across the ship; thus they tend to prevent the rolling of the ship. The direction of a torpedo is also controlled by a gyroscope.

2. CENTRIPETAL FORCE AND ITS USES

It "seeks the center." The equal but opposite reaction to centrifugal force is centripetal, or center-seeking, force. Centrifugal force usually receives more consideration because its effects are more readily visible. There is a force of cohesion which keeps a whirling wheel from flying apart but this centripetal force is not noticed unless the wheel does fly apart. It is centripetal force, then, that holds rotating bodies together. The strength of the material of which a rotating object is made determines the limit of centripetal force for that object. The materials of such rotating objects as airplane propellers must be of high tensile strength in order that a great centripetal force may be exerted at a high velocity of rotation.

SUMMARY

1. Gravitation is the attraction between two masses. The force of attraction between two bodies is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.

2. The gram of force and the pound of force are gravitational units of force.

3. The resultant of two or more forces is that single force which could produce the same effect as the two or more forces acting together. The resultant of forces acting in the same direction is their sum; the resultant of forces acting in opposite directions is their difference.

4. The resultant of two concurring forces acting at an angle is equal to the diagonal of the parallelogram of which the forces are adjacent sides. The equilibrant is that force which produces equilibrium; it is equal to the resultant and opposite in direction.

5. A single force may be resolved into two or more com-

ponents. In such a case, the single force is represented by the diagonal of a parallelogram of which the two components are sides.

6. The center of gravity of a body is that point at which all its weight appears to be concentrated.

7. An object is in equilibrium when the resultant of all the forces acting upon it is zero. The stability of an object is increased by broadening its base and by lowering its center of gravity.

8. Motion may be rectilinear or curvilinear. Velocity is the rate of motion. Acceleration is the rate of change of velocity.

9. If the acceleration is constant, velocity = acceleration × time; space passed over = $\frac{1}{2}at^2$.

10. The laws of accelerated motion apply to uniformly retarded motion. Freely falling bodies are uniformly accelerated. The acceleration, which is due to gravity, is approximately 980 cm. per second per second.

11. The period of vibration of the pendulum is independent of the mass, material, or amplitude; it is directly proportional to the square root of the length, and inversely proportional to the square root of the acceleration due to gravity.

12. Newton formulated three laws of motion: (*1*) Every body continues in its state of rest or uniform motion in a straight line unless compelled by some external force to change that state. (*2*) Rate of change of momentum is proportional to the acting force and takes place in the direction in which the force acts. (*3*) For every action there is an equal and opposite reaction.

13. Momentum is the quantity of motion. It equals the product of the mass times the velocity.

14. Centrifugal force increases with the mass; it is directly proportional to the square of the velocity; it is inversely proportional to the radius of curvature.

15. Centripetal force is the reaction to centrifugal force.

How many of the following terms can you define or explain?

Gravity
Composition of force
Resultant
Equilibrant
Resolution of force
Rectilinear motion
Curvilinear motion
Acceleration
Pendulum
Center of oscillation
Center of percussion
Inertia
Momentum
Range
Trajectory
Centrifugal force
Centrifuge
Centripetal force

SELF-TESTING EXERCISES

ANSWER THESE QUESTIONS

On a separate sheet of paper numbered from 1 to 8 write the letters for the phrases that answer the following questions correctly.

1. Which of the following statements is true about the gram of force? (*a*) It is greater at the North Pole than it is at Omaha, Nebraska; (*b*) it is constant at all points on the earth which are at sea level; (*c*) it becomes greater when lowered beneath the surface of the earth.

2. What is the correct reason why a 600-lb. weight on the earth would weigh only about 60 lb. on the moon? (*a*) The moon is smaller than the earth; (*b*) the moon is of smaller mass than the earth; (*c*) the moon is more dense than the earth.

3. If the attraction between the earth and a car is 3000 lb., the car attracts the earth with how much force? (*a*) Less than 3000 lb.; (*b*) exactly 3000 lb.; (*c*) more than 3000 lb.; (*d*) zero lb.

4. Which of the following statements is true of the weight of a body placed at the center of the earth? (*a*) It would be very great; (*b*) it would be the same as at the earth's surface; (*c*) it would be zero.

5. Which of the following terms correctly describes a single force which could produce the same effect as two or more forces acting together? (*a*) Equilibrant; (*b*) composition; (*c*) resultant.

6. Disregarding air resistance, which of the following statements is true about the rate of fall of a freely falling body? (*a*) It depends upon the size of the body; (*b*) it depends upon the weight of the body; (*c*) it depends upon the distance from the surface of the earth.

7. In which of the following ways may the acceleration of a car be expressed? (*a*) In miles per hour; (*b*) in feet per second; (*c*) in miles per hour per second.

8. Which of the following terms denotes the reason why a car may skid or overturn on a road curve? (*a*) Centripetal force; (*b*) centrifugal force; (*c*) acceleration.

COMPLETE THESE STATEMENTS

On a separate sheet of paper numbered from 1 to 11 write the words needed to fill correctly the blank spaces in the following sentences.

If an airplane is flying at a constant speed the sum of all the forces acting on it is . . (1) . . . The . . (2) . . of two or more forces is always equal and opposite to their . . (3) . . . If an object moves in a straight line, its motion is called . . (4) . . . The momentum of recoil of a gun equals the momentum of the . . (5) . . . A pendulum vibrates . . (6) . . at the top of a mountain than it does at the base. The stopping distance for a car traveling 60 miles per hour is . . (7) . . times that of the same car traveling 30 miles per hour. The effective length of a pendulum is the distance between its center of suspension and its center of . . (8) . . . The curved path of a projectile is called its . . (9) . . . Objects weigh less at the equator than at either pole because the earth is . . (10) . . at the poles and also because of the . . (11) . . force due to the rotation of the earth.

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 7 write a T *or an* F *to show whether each statement is true or false.*

1. The path of a pendulum bob is an example of curvilinear motion.
2. One driver hits a tree when driving 20 miles per hour. A second driver hits a tree when driving 40 miles per hour. The force of impact in the second case is twice that of the first case.
3. The product of the mass of a body times its motion is quantity of motion.
4. Centrifugal force is inversely proportional to mass.
5. Centripetal force is equal but opposite to the accompanying centrifugal force.
6. Acceleration is directly proportional to the acting force.
7. A rifle bullet is fired horizontally. It drops 16.08 ft. during the first second.

QUESTIONS

1. If a hole were bored through the earth and a ball dropped into it, where do you think it would come to rest? Explain.

2. Would a gram of force at the sun be greater than a gram of force at the earth's surface?

3. Is a gram of force greater at the earth's surface than it is at the center of the earth? Give a reason for your answer.

4. Why would you lower the handle of a lawn mower in pushing it through tall grass? Use a diagram to clarify your explanation. Does your diagram seem to indicate that a boy works to better advantage than a man when mowing the lawn?

5. Does a man weigh more at the North Pole or at the equator?

6. Does he weigh more on top of a mountain or at its base?

7. A spring balance is graduated to read pounds at New York. If this balance were used to weigh meat at the North Pole, would you get more meat or less in a 5-lb. roast? Suppose a platform balance were used; would you get more meat at New York or at the North Pole?

8. A hammock is 8 ft. long. Is it more likely to break if the ends are attached to posts 5 ft. apart or 7 ft. apart? Use a diagram in your explanation.

9. Is it easier to pull yourself up if you grasp the bar of a trapeze with your hands 1 ft. apart or 2 ft. apart? Explain. Try the experiment.

10. Why is it easier to throw a curved ball than a straight one?

11. Compare the force of attraction between two objects when held 1 ft. apart and when held 2 ft. apart.

12. Explain the principle of the rotary lawn sprinkler.

13. If action equals reaction, why is it not so dangerous to receive the "kick" of a gun as to be struck by the bullet?

14. Why is the head of a hammer tightened by pounding on the end of the handle?

15. If a clock gains time, would you raise or lower the pendulum bob? Explain.

16. Does a pendulum vibrate faster at the top of a mountain or at its base? Give a reason for your answer.

17. Explain why a sharp curve of short radius is more dangerous to the driver of a car than a curve of long radius.

18. How does centrifugal force affect the weight of objects at the equator?

19. A hammer sometimes "stings" the hand. Explain.

20. How would you locate the center of percussion of a baseball bat?

21. How do steamships and submarines utilize the gyroscopic principle?

22. Could David have thrown a stone farther with a 3-ft. or a 4-ft. cord attached to his sling? Explain.

23. If a man is strong enough to swing a 5-ft. baseball bat, can he drive a ball farther with it than with a bat of the usual length? If so, why not use such a bat?

24. Other things being equal, does a long-armed baseball pitcher have an advantage over his shorter-armed opponent?

25. Give a reason why you would expect an object at the top of a tall mountain to fall more rapidly than at its base. Give a reason why you would expect it to fall less rapidly.

26. Does the speedometer of an automobile show velocity or acceleration? Explain.

27. Since the earth's attraction for a 5-lb. iron weight is five times as much as it is for a 1-lb. iron weight, why does not the 5-lb. weight fall five times as fast?

28. Water is poured from a pitcher at a height of a foot or more. Explain why the stream of water becomes much reduced in size.

29. If a car running 20 mi. per hr. can be stopped in 17 ft., what is the required stopping distance when the same car is traveling 40 mi. per hr.?

30. Compare the scientific accomplishments of Aristotle with those of Galileo.

31. Why is it necessary to give the acceleration due to gravity as 32.16 ft. per sec. per sec. at New York City? Is it the same at the tropics?

32. If the magnitude of the centrifugal force of a rotating object is known, how would you find its centripetal force?

33. Why is centrifugal force spoken of more commonly than centripetal?

PROBLEMS

In solving problems pertaining to freely falling bodies, use $g = 980$ *cm. per second per second, or* $g = 32$ *ft. per second per second.*

1. One force of 40 gm. acts in a westerly direction upon a given point, and a second force of 35 gm. acts northerly. Represent graphically, and calculate the resultant.

2. By means of a graph, find the resultant of two forces acting upon the same point, if one force of 28 lb. acts southerly, and the other force of 40 lb. acts westerly. Calculate the resultant of the two forces. How do the two answers compare? Which method do you think is more accurate?

3. Given two forces, 12 and 15 lb. each, acting upon the point P.

Find their resultant: (*a*) when the angle between them is 180°; (*b*) when the included angle is 120°; (*c*) when it is 90°; (*d*) when it is 60°; (*e*) when it is zero.

4. A force of 30 lb. acts easterly upon the point P. A second force of 50 lb. acts southwesterly. Represent graphically and show the length and direction of the equilibrant. What is the value of the resultant?

5. A man who weighs 180 lb. runs with a speed of 20 ft. per second. A second man who weighs 140 lb. runs at a speed of 30 ft. per second. What is the momentum of each one?

6. One pendulum makes a vibration in 0.5 sec., and another pendulum makes a vibration in 0.9 sec. How do their lengths compare?

7. Find the resultant of two 50-lb. forces when the included angle between them is 60°.

8. An inclined plane is 12 ft. long and one end is 4 ft. higher than the other. A weight of 300 lb. rests on the plane. Find the value of the force tending to break the plane, and of the force needed to keep the weight from sliding down the plane.

9. Find the equilibrant of two forces of 200 lb. each, if the angle included between the two forces is 45°.

10. If a pendulum 16 cm. long makes a single vibration in 0.4 second, how long will it take for a pendulum 49 cm. long to make a single vibration?

11. How long must a pendulum be to make a single vibration in 0.5 sec., if g equals 980 cm. per sec. per sec.?

12. An airplane travels at a velocity of 100 mi. per hr. Express its velocity in ft. per sec.

13. Howard Hughes flew from New York to Paris, a distance of 3600 mi. in 16 hr. and 35 min. What was his speed in mi. per hr.?

14. In his round-the-world flight Hughes covered 14,548 miles in 91.5 hours, including time for refueling. What was his average speed in miles per minute?

15. In a motor-paced bicycle race, a rider covered a distance of 40 mi. in 55 min. What was his velocity in mi. per hr.? In ft. per sec.?

16. A man runs 100 yd. in 9.6 sec. At that rate how long will it take him to run a mile? What is the record for the mile run?

17. A train 550 yd. long runs at 45 mi. per hr. How long will it take the train to pass completely over a bridge 990 ft. long?

18. How far does a body fall in 15 sec.? With what velocity does it strike the earth?

19. How far does a body fall in 8 sec.? In 1 sec.? In $\frac{1}{2}$ sec.? In $\frac{1}{4}$ sec.?

20. How far does a body fall in 9 sec.? In the ninth second? Can you solve these problems by two methods? Do you get the same answer both times?

21. A bomb is dropped from a height of 16,000 ft. How soon will it reach the earth?

22. With what velocity does the bomb of problem 21 strike the earth?

23. The opening near the top of the Washington Monument is 504 ft. above the ground. With what velocity does a baseball dropped from this opening strike the earth?

24. A ball weighing 16 lb. is swung by a cord 4 ft. long. If the velocity is 20 ft. per sec., what pull in pounds does it exert on the cord?

25. A car weighing 3600 lb. rounds a curve of 80-ft. radius at 20 mi. per hr. What is the force in lb. tending to throw the car off the road?

26. If the car of problem 25 rounds the curve at a speed of 45 mi. per hr., what is the centrifugal force in pounds?

27. Suppose that the car of problem 25 is traveling 60 mi. per hr. around the curve. What is the centripetal force in pounds?

VIII

Machines Use Heat Energy

A. SOURCES OF HEAT

On this planet we receive heat from a number of different sources. The most important are the sun, the chemical energy of fuels, mechanical energy, and electricity.

1. THE SUN

Directly or indirectly, nearly all the earth's heat may be traced to the sun as its origin. Plants need the heat from the sun for their growth, and animals are dependent upon plants. Although on a hot, sultry day in July we may appear to be getting a large amount of the sun's heat, it is estimated that the earth as a whole receives only one two-billionth of all the heat which the sun gives off.

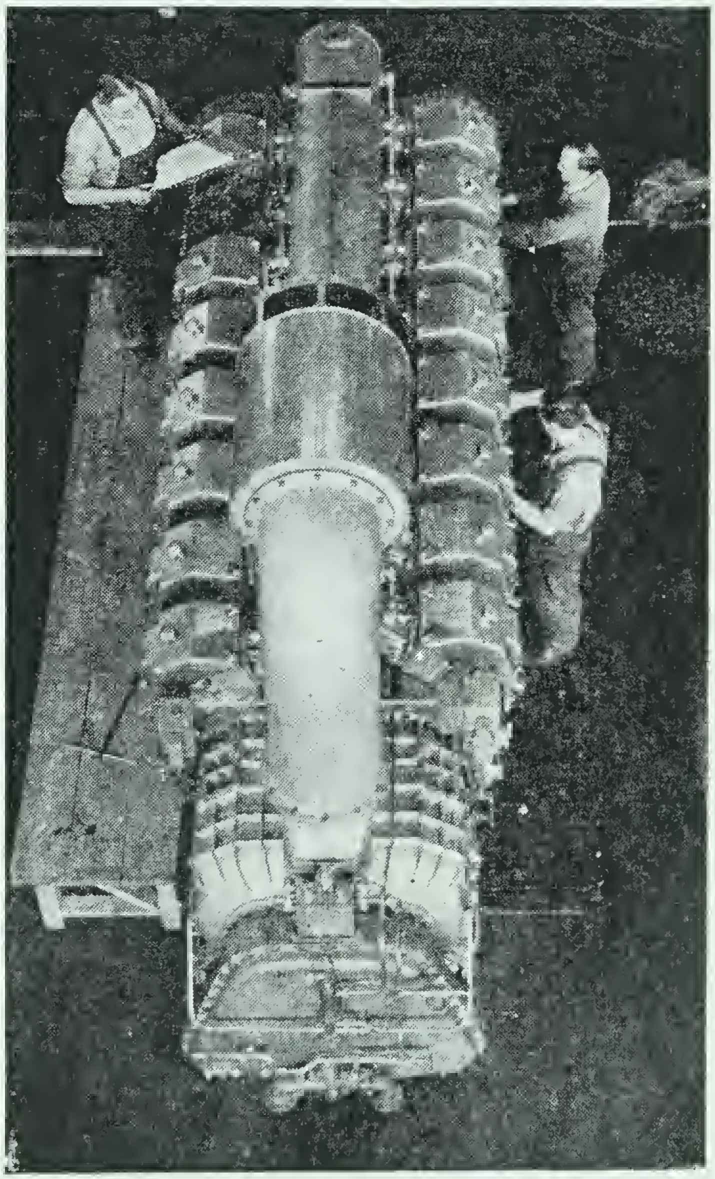
2. CHEMICAL ENERGY OF FUELS

For our chief source of artificial heat, we depend upon the combustion of wood, coal, oil, or gas. The oxygen of the air combines with the burning fuel, while both heat and light are given off. The oxygen we breathe unites with the food we eat fast enough to supply the heat needed to keep the temperature of our bodies at about 98.6° F., summer or winter.

3. MECHANICAL ENERGY

Mechanical energy can be changed into heat. *Friction* results in wasted work, and the energy from such wasted work is changed into heat energy. We rub the head of a match on emery paper and heat it by friction to its kindling temperature. You may climb a rope and then let it slip through your hands as you descend. Your hands will be heated decidedly and probably blistered.

Brake linings sometimes burn out from the heat produced by friction. When a lead bullet is fired against a hard-steel plate, it may be heated hot enough to melt the lead by *impact.* The moving bullet has kinetic energy. When it is stopped suddenly the kinetic energy is changed into heat energy. If we use a compression pump to inflate a tire, the cylinder of the pump becomes hot. Part of this heat comes from the friction of the piston moving in the cylinder, but the larger portion comes from the heat of *compression.* Gases become decidedly hot when they are compressed, and they cool off when allowed to expand again. Due to a decrease of pressure as altitude increases, a rising mass of warm air expands and becomes cooler. This may continue until the temperature of the air is lowered to its dew point, the temperature at which droplets of water begin to form. The same principle is used in the mechanical refrigerator. A gas is liquefied by means of a pressure pump, then allowed to expand into tubes surrounding the cooling element inside the refrigeration compartment.



Courtesy of Westinghouse

FIG. 8–1. The Diesel engine utilizes inexpensive fuel.

How does the four-cycle Diesel engine work? The formation of heat by pressure has an important application in the *Diesel* engine. The four-cycle Diesel engine differs little in operation from the four-cycle gas engine. It is designed to operate on oils that are heavier and cheaper than gasoline. During the first cycle, pure air is drawn into the cylinder. On the upstroke, the piston compresses the air to more than 30 atmospheres. The heat of such great compression makes the air so hot that it will kindle the fuel and no electric spark is needed. Just before the beginning of the third cycle, the fuel valve opens to admit the oil vapors, which are forced into the cylinder by an air blast of high compression. The hot air ignites the fuel which burns during this power stroke of the engine. The waste gases escape during the exhaust stroke just as they do with a gas engine. The Diesel engine is widely used on submarines, some ocean vessels, and in power plants. (See Fig. 8–1.) Some of the streamlined trains that are now coming into extensive use are powered by Diesel engines. Considerable experimental work has been done in attempting to adapt the Diesel engine to use in automobiles. The promise of a motor which can use cheaper fuel is alluring, and a simplified ignition system is desirable.

How does the semi-Diesel engine work? In a *semi-Diesel* engine the compression is not so great. A firing pin is heated red hot and screwed into the end of the firing chamber in order to start the engine. Air is admitted during the first stroke and compressed during the second stroke of the piston. The fuel oil is forced into the cylinder just before the completion of the compression stroke. It vaporizes instantly as it strikes the hot walls, and it is kindled by the hot firing pin. Such engines find considerable use in small power plants.

4. ELECTRICITY

Another common source of heat is in the transformation of electrical energy into heat energy. We are all familiar with the electric curling iron, the electric hair drier, the electric flatiron, the electric bread-toaster, the electric waffle-iron, the electric coffee percolator, the electric grill, and the electric heater. (See Fig. 8–2.) In some cases, the electric heating pad takes the place of the hot-water bottle in the sick room. A wire heated electrically is used to cauterize wounds or to burn away growths of surplus tissue. Trolley cars are usually heated by electric heaters. In the majority of these electrical heating appliances, coils of high resistance wire, usually made of *nichrome*, are so grouped that a great deal of heat is concentrated in one place. At the prices charged for electrical energy in many places, it costs more to heat or cook by electricity than it does by the use of gas or some other fuel. Power companies in some regions are beginning to make lower rates to small consumers who use electricity for refrigeration, for operating washing machines, and for cooking.

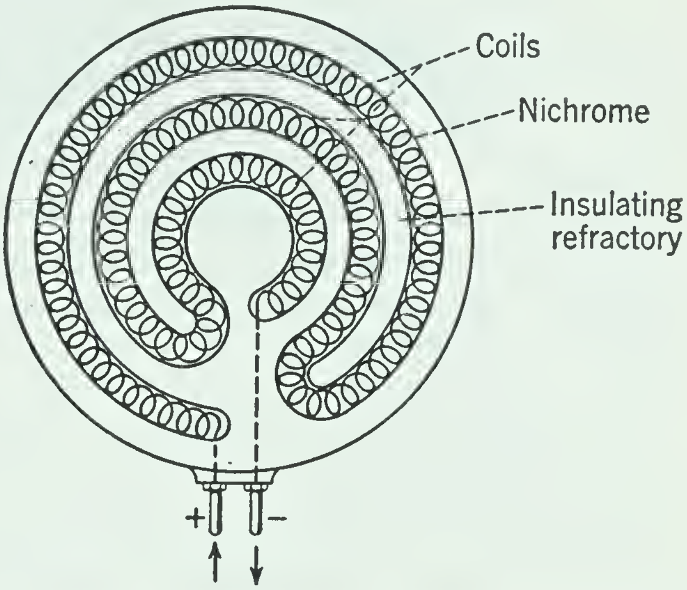


Fig. 8–2. Electric heater, with its coils of nichrome wire. Nichrome is an alloy of nickel, iron, and chromium.

If two pieces of wire are placed end to end and a current is passed through them, the heat developed at the point of contact is sufficient to *weld* them into one piece. You have probably seen trolley company employees using electric welding on the tracks. Current for such a purpose is drawn from the trolley wire. At one time, metal plates used for construction work were riveted together. Now the edges of such metal plates are usually welded together by means of the electric current.

Two types of electric furnace are in use.

(1) *Resistance furnaces.* In furnaces of this type, an electric current is passed through a coil of wire made of platinum, nichrome, tungsten, or molybdenum which is wound upon some refractory material. The substance to be heated is placed inside the coil. Possibly your dentist uses such a furnace in making artificial teeth. In such a resistance furnace a temperature of from 1000° C. to nearly 2000° C. can be obtained.

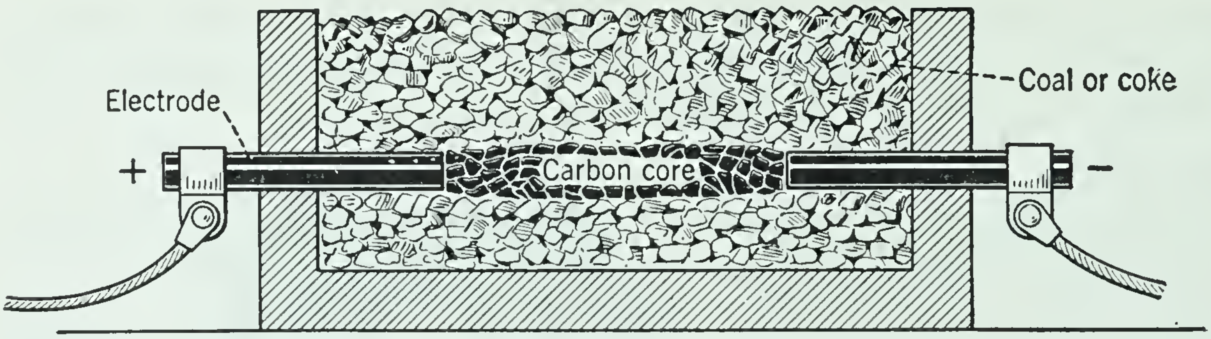


FIG. 8–3. The carbon core offers resistance in this furnace used for making graphite. Furnaces of this type are also used for making calcium carbide and Carborundum.

In another type of resistance furnace, the heat is produced by the resistance which the material in the furnace itself offers to the passage of the current between the electrodes, which are placed at the opposite ends of the furnace. Furnaces used for making calcium carbide, Carborundum, and artificial graphite are of this type. (See Fig. 8–3.)

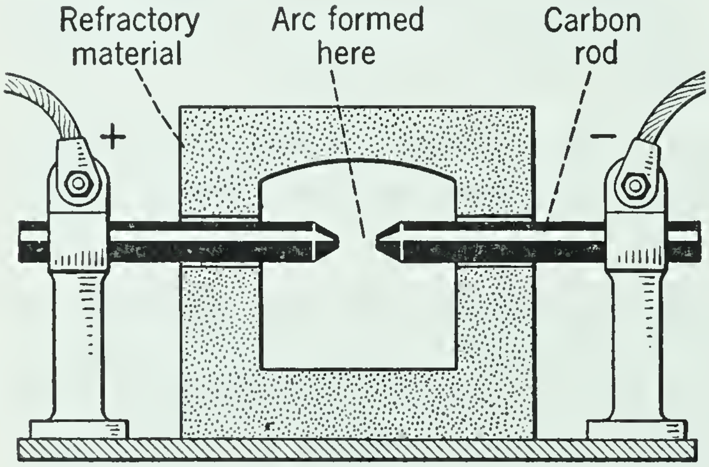


FIG. 8–4. The arc type of electric furnace. The temperature produced may reach 3500° C.

(2) *Arc type furnaces.* Exceedingly high temperatures are obtained in the arc type furnaces. The temperature is estimated at about 3500° C. The electric arc is formed between two carbon rods in a refractory crucible in which the contents to be heated are placed. (See Fig. 8–4.) At one time, heat from an arc type of furnace was used to make nitrogen compounds from the free nitrogen present in the air. An electric furnace used for making steel is a kind of combination arc and resistance type.

DEMONSTRATIONS. 1. Drop a small piece of sheet copper or copper turnings into a test tube containing concentrated nitric acid. After noticeable action has taken place, feel the bottom of the test tube. Note how its temperature has changed. What is the source of the heat given off?

2. Burn a wood splint. By means of tongs or forceps hold a strip of magnesium ribbon in the flame of a Bunsen burner until it becomes ignited. What is the source of heat in these two cases?

3. Pound a piece of lead with a hammer, then feel it to see if its temperature has changed. Then rapidly bend a piece of iron wire back and forth. Did its temperature change in the place where you bent it? What is the source of the heat in these two cases?

4. Ignite a piece of tinder in the end of a piston by quickly forcing the piston into a fire and compression tube. What is the source of the heat that ignited the tinder?

5. Connect two dry cells in series and pass a current through a short piece of nichrome wire. Note the wire's change in temperature. What is the source of this heat?

B. WHAT IS HEAT?

1. THEORY OF HEAT

Heat is a form of energy. In the year 1799 Sir Humphry Davy performed one of his striking experiments. He melted two pieces of ice by rubbing them together vigorously. In that way he proved that *heat is really a form of energy.* Before his experiment, heat was considered to be a weightless fluid called *caloric.*

From our study of the kinetic theory of matter we know that the temperature of a body rises as the velocity of its moving molecules increases. Conversely, a decrease in molecular velocity causes a fall in temperature. The Indians used to start fires by rubbing two sticks together until enough heat was produced to kindle them. Boy Scouts now use "fire sticks" in a similar manner to start fires when camping. Hence we conclude that heat may be defined as kinetic energy due to molecular motion.

2. HEAT DIFFERS FROM TEMPERATURE

How to distinguish between heat and temperature. Although heat and temperature are related, we must learn to distinguish between them. A burning match has a much higher temperature than a steam radiator, but it does not give as much heat for warming a room. We may dip a cupful of boiling water from a tubful of boiling water. The temperature of the water in the cup is the same as that in the tub, but we could melt more ice with the tubful of water than we could with a cupful, because it contains *more heat.* Ten pounds of water at 80° F. will melt more ice than one pound of water at 100° F. The former has more heat, but the latter has the higher temperature. (See Fig. 8–5.)

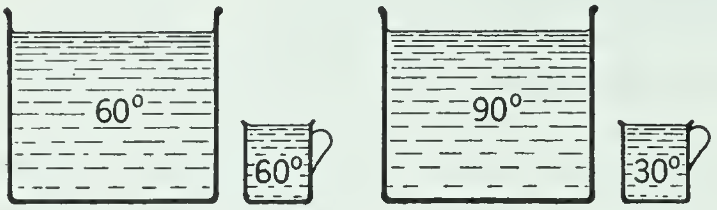


FIG. 8–5. In one case the temperatures are the same, but the quantities of heat are unequal. In the other case, both are unequal.

The temperature of a body depends upon the *average kinetic energy* of all its molecules. Temperature is measured in *degrees.* The heat of a body depends upon the *sum total of all the kinetic energies* of its molecules. Heat is measured in *calories* or *British thermal units.*

A small radiator with only a few sections may have the same temperature as a large radiator with many sections, but it cannot supply so much heat to a room. From these observations, we learn that it is possible for a body to have a high temperature and little heat; it may have a high temperature and much heat; it may have a low temperature and little heat; or it may have a low temperature and a large quantity of heat.

Is our temperature sense reliable? We use the terms "hot," "warm," "cool," and "cold" to indicate temperature. From two or three examples, it is easy to show why they are relative and mean little. A room that feels comfortable to a person who has been resting seems uncomfortably hot to a person who has been exercising vigorously. Suppose that you have three adjoining rooms, "hot," "warm," and "cold," respectively. If a person goes from the first room into the second, he will tell you that the room is "cold," but if he goes from the third into the second, he will then say that the room is "warm." His sensation of "hot" and "cold" was influenced by his environment.

Suppose you try the following experiment. Take three tumblers and fill the one at your left with *hot* water, the middle one with *warm* water, and the one at your right with *ice* water. For a few moments hold a finger of your left hand in the hot water and a finger of your right hand in the ice cold water. Then dip both fingers into the tumbler of warm water. You will have the strange sensation of feeling that the warm water is both warm and cold at the same time, for it will feel cold to your left finger and warm to your right. Because *our temperature sense is unreliable,* we need to have thermometers to measure the degree of heat, as we shall see later.

How is heat measured? We use thermometers to measure temperatures, but they cannot be used to measure heat. We have learned, too, that two substances may have the same temperature, but different quantities of heat. When a man buys coal, he is interested to know how many *heat units* he has bought, and not how high a temperature the burning coal will produce. It is possible to measure in the laboratory the *heat content of a weighed sample of fuel by finding the effect which it can produce.* If we find, for example, that one sample of coal will heat one liter of water *one* degree, and that another sample of coal will heat one liter of water *two* degrees, then we know that the heat content of the latter is just double that of the former. Once again, we shall use pure water *as a standard* in the definition of heat units.

The calorie is the common unit for the measurement of heat. We talk a great deal about *calories* and the number that we eat each day. What does the calorie mean to a physicist? *The calorie is the quantity of heat needed to warm one gram of water through one degree Centigrade.* When one gram of water cools through one degree Centigrade, *it loses one calorie of heat.* To warm one gram of water ten degrees one would need ten calories, and it would also take ten calories to raise the temperature of ten grams of water one degree Centigrade. One gram of a good grade of soft coal gives out about 8000 calories as it burns.

What does the calorie mean to the biologist? In the study of biology and in dietetics the *large Calorie* is used. We shall spell it with a capital *C* to avoid confusion. The large Calorie is equal to 1000 small calories. It is the amount of heat needed to raise the temperature of 1000 gm., or 1 kgm. of water, 1° C. When we say, "A thick slice of bread furnishes 100 Calories," we mean that the bread, if totally oxidized, would supply the body with enough heat to raise the temperature of 1000 gm. of water 100° C. Or, it would raise the temperature of 100,000 gm. (100 kgm.) 1° C. The Calorie is a measure of the fuel value of the food. It is sometimes called the *kilocalorie*.

The English system uses the B.T.U. The heat unit used in the English system is the *British thermal unit* (*B.T.U.*, or *Btu.*), which is the *amount of heat required to raise the temperature of 1 lb. of water 1° F. One B.T.U. equals 252 calories.*

The measurement of heat will be studied in greater detail in Chapter X.

SUMMARY

1. The sun, chemical action, friction, impact, and compression are the chief sources of heat.

2. Heat is the sum of the kinetic energies of all the molecules of a body. The temperature of a body is the average kinetic energy of its molecules.

3. The average kinetic energy of the molecules in a substance is measured in degrees by means of a thermometer.

4. The metric unit of quantity of heat is the calorie, which is the amount of heat required to raise the temperature of one gram of water through one degree Centigrade.

5. The English unit of quantity of heat is the British thermal unit (B.T.U.), which is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit.

How many of the following terms can you define or explain?

Heat
Temperature
Calorie
B.T.U.

SELF-TESTING EXERCISES

Complete These Statements

On a separate sheet of paper numbered from 1 to 12 write the words needed to fill correctly the blank spaces in the following sentences.

Friction usually causes ..(1).. energy to be changed into ..(2).. energy. Burning wood changes ..(3).. energy into heat. Heat may be generated by ..(4).. a gas. ..(5).. energy is changed to heat energy by means of the arc type of furnace. Quantity of heat is measured in ..(6).. but intensity of heat is measured in ..(7)... The large calorie equals ..(8).. small calories. The fuel value of foods may be expressed in ..(9)... Directly or indirectly the ..(10).. is the source of all heat. Diesel engines depend upon heat of ..(11).. to ignite the gas mixture. Very high temperatures can be obtained by means of the ..(12).. type of furnace.

QUESTIONS

1. Why do sparks sometimes fly from a car wheel when the brakes are applied?
2. Sometimes the brakes of an automobile catch fire when the driver is descending a long grade. Explain, and tell how such a condition may be avoided.
3. Give an example of a body that has a low temperature and a large quantity of heat. Give an example of a body that has a high temperature but contains little heat.
4. Air must be cooled before rain falls. At the tropics the air currents are descending. How do you account for the arid regions in Australia?
5. Occasionally a train is delayed because of a "hot box." What is a "hot box," and how is it caused?
6. Explain how chemical energy can be expressed in heat units.

IX

Heat Produces Expansion of Solids, Liquids, and Gases

A. SOLIDS

1. CAUSE OF EXPANSION

Collision of molecules in motion makes them move farther apart. In Chapter VIII you learned that by the kinetic theory heat is molecular motion. When a substance is heated, the rate of motion of its molecules is increased. This increased molecular motion causes in turn an increase of molecular collisions, and these collisions make the molecules move farther apart from one another. The resulting increase in the volume of a heated substance is called *expansion.*

Examples of expansion in heated solids. If you are a good observer, you will have noticed that telephone wires sag more in summer than in winter. You will find, too, that the spaces between the ends of railroad rails are wider in winter than in summer. Sometimes wires used for fences and for telephone or telegraph lines contract so strongly in cold weather that they break. With few exceptions, *solids expand when they are heated and contract when cooled.*

How great is the force of expansion? The force of expansion or contraction is enormous. Broken wires in winter, cracks in pavements, and the bursting of tires when highly heated all testify to the great force exerted by a change in temperature. Concrete walks buckle under the force of expansion. The magnitude of this force seems to be limited only by the breaking strength of the material at the given temperature. With a steel bar of 1 sq. in. cross-sectional area, the force may be nearly 70 tons.

How does expansion affect density? Heating a gas, a liquid, or a solid does not change its weight. But if its volume is increased by heating, then its density must be reduced. For this reason, we find that the warmer, lighter air of a room is near the ceiling. Hot water accumulates at the top of the tank. When we study the methods of distributing heat from one place to another, we shall find that the fact that gases and liquids are less dense when hot than when cold plays an important role.

When a confined gas is heated but cannot expand, the pressure which the gas exerts is increased. A pneumatic tire pumped up on a cool morning may show a gauge pressure of 35 lb. per sq. in. If the tire stands in the sun so that the temperature of the air inside is increased 20 or 30 degrees Centigrade, it may show a pressure of 38 or 39 lb. per sq. in. Raising the temperature increases the velocity of the molecules, and they bombard the inner walls of the tire more vigorously, thus increasing the pressure.

At room temperature, the iron ball of Figure 9–1 passes easily through the ring. If we heat the ball strongly, it cannot pass through the ring at all. Next, let us heat the ring strongly, and we find that the heated ball will pass through the ring. If we pour cold water on the ring to cool it, the ring will contract so much that the hot ball cannot pass through it. Rubber is one of the important exceptions to the general rule that solids expand when heated and contract when cooled. A few others are known.

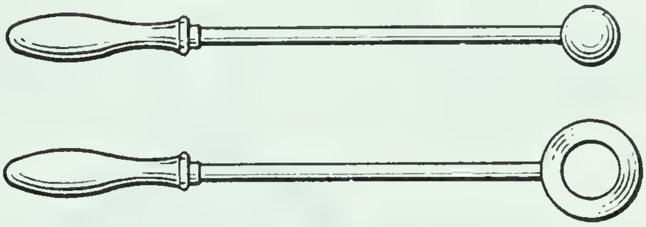


Fig. 9–1. The cold ball passes through the ring, but the heated ball cannot.

Demonstration. Try the ball and ring experiment shown in Figure 9–1.

2. COEFFICIENT OF EXPANSION

How much do solids expand? To answer a question of this kind, it is necessary to experiment. In the laboratory it can be shown that one foot of aluminum wire will expand more than twice as much as one foot of iron wire, if each one is heated one degree. That number or factor which shows the *actual increase in unit length of a solid when it is heated one degree is called its coefficient of linear expansion.* For example, 1 ft. of aluminum will expand 0.000023 ft. when its temperature is raised 1° C. The same increase in temperature will cause 1 ft. of iron to increase 0.000011 ft. Table 7 in Appendix A shows the coefficient of expansion for several solids. This table gives the coefficient of expansion for *Centigrade degrees.* The coefficient of expansion for *Fahrenheit degrees* will be just $\frac{5}{9}$ as much.

If 1 ft. of aluminum wire expands 0.000023 ft. when heated 1° C., then 10 ft. will expand 10 times as much, or the increase will be 0.00023 ft. If 10 ft. of wire are heated 10° C., the increase in length will be ten times as great as for 1° C., or 0.0023 ft. Thus we find that the *total increase in length of a solid when heated must be equal to its length times its change in temperature times its coefficient of linear expansion.*

PROBLEM. An iron rod is 65 cm. long at 0° C. How much will it expand when heated to 80° C.? What will be its length at 80° C.?

Solution. From the table we see that 1 cm. of iron expands .000011 cm. when heated 1° C.; 65 cm. will expand 65 × .000011 cm., or .000715 cm., when heated 1° C.; the change in temperature is 80 degrees, so the actual increase would be 80 × .000715 cm., or .0572 cm. The length of the rod at 80° C. would be 65.0572 cm. (Original length plus expansion.)

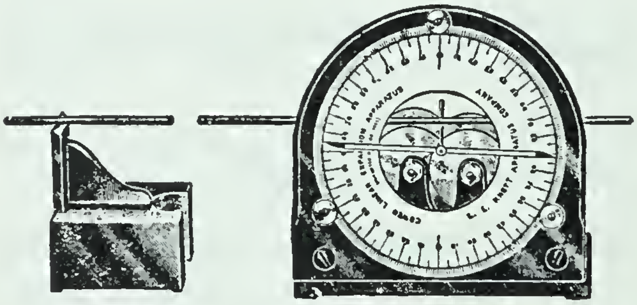


FIG. 9–2. Cowan's apparatus.

You can determine the coefficient of expansion of a tube of aluminum by using a Cowan's apparatus; one is shown in Figure 9–2.

With a micrometer caliper measure the diameter of the axis of the pointer, and place it on the rollers so the pointer stands at the zero of the circular protractor. Use a rubber tube to connect the left end of the aluminum tube to a steam boiler, and then place the tube on the apparatus as shown in the figure. See that the groove in the tube rests on the edge of the metal support. The protractor portion of the apparatus should be near the other end of the tube. Measure as accurately as possible that portion of the length of the tube which lies between the two points of support. Take the temperature of the room.

Pass steam through the tube for at least five minutes. As the tube expands, it rolls the axis through a portion of its circumference. Suppose the pointer moves over a space of 36 degrees. Then the rod must have expanded an amount equal to 36/360, or 0 1, of the circumference of the axis. If n represents the number of degrees over which the pointer moves, and d the diameter of the axis, then $\frac{n}{360} \times \pi d =$ the total increase in the length of the rod. (See Appendix C.)

Find the temperature of the steam, and divide the total increase in length by the change in temperature of the brass tube (steam temperature minus room temperature) in degrees Centigrade. The quotient is the expansion of the entire tube per degree Centigrade. Divide this quotient by the length of the tube to find the coefficient of linear expansion.

Do solids expand in all directions? It is important to keep in mind the fact that solids when heated not only increase in length but they also expand in width and thickness. The *coefficient of superficial expansion*, or the increase in unit area per degree, is slightly more than *double* the linear coefficient. The buckling of metal roofs and concrete sidewalks when strongly heated is due to the expansion in area. The *coefficient of cubical expansion*, or the increase in volume when a solid is heated one degree, is slightly more than *three times* the coefficient of linear expansion.

What is the effect of unequal heating? If boiling water is poured quickly into a thick-walled glass tumbler, the tumbler will probably crack. The inside is heated and expands before the outside does. Men sometimes crack up large boulders by building a fire around them to heat them strongly. Fragments and chips of rock then split and break off when cold water is thrown upon the hot boulder. Unequal heating often causes solids to break, because one portion expands more than another.

Can expansion of solids be made useful? Sometimes walls spread apart and threaten to fall. A long iron rod may be put through, heated strongly, and the nuts at the ends screwed on tightly. As the rod contracts upon cooling, the walls are pulled together. (See Fig. 9–3.) Rivets are heated red hot before they are used to rivet steel plates together. As they cool they contract and make a very tight joint. The expansion and contraction of metals is used to open and close valves.

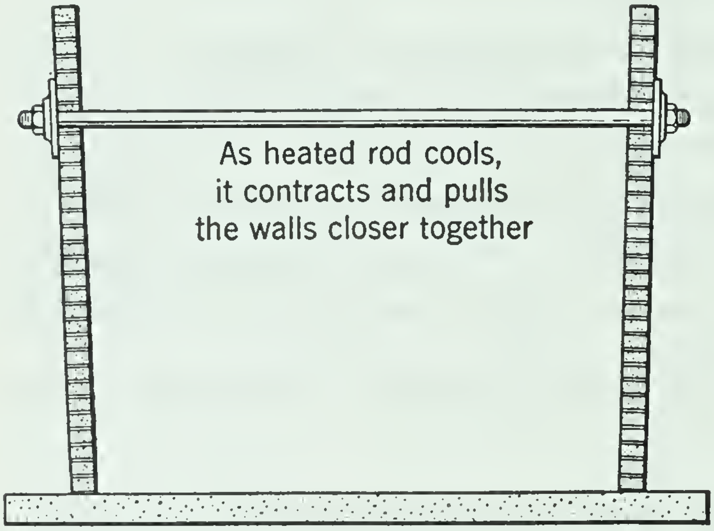


Fig. 9–3. As the heated rod cools it contracts and straightens the walls.

In one type of automatic water heater, a rod of *invar*, a metal of low coefficient of linear expansion, is used inside a copper tube to regulate the amount of gas needed to keep the water in the hot-water tank at the desired temperature. As the copper tube expands it gradually closes the valve regulating the flow of gas, and as it cools it permits the valve to open again. (See Fig. 9–4.)

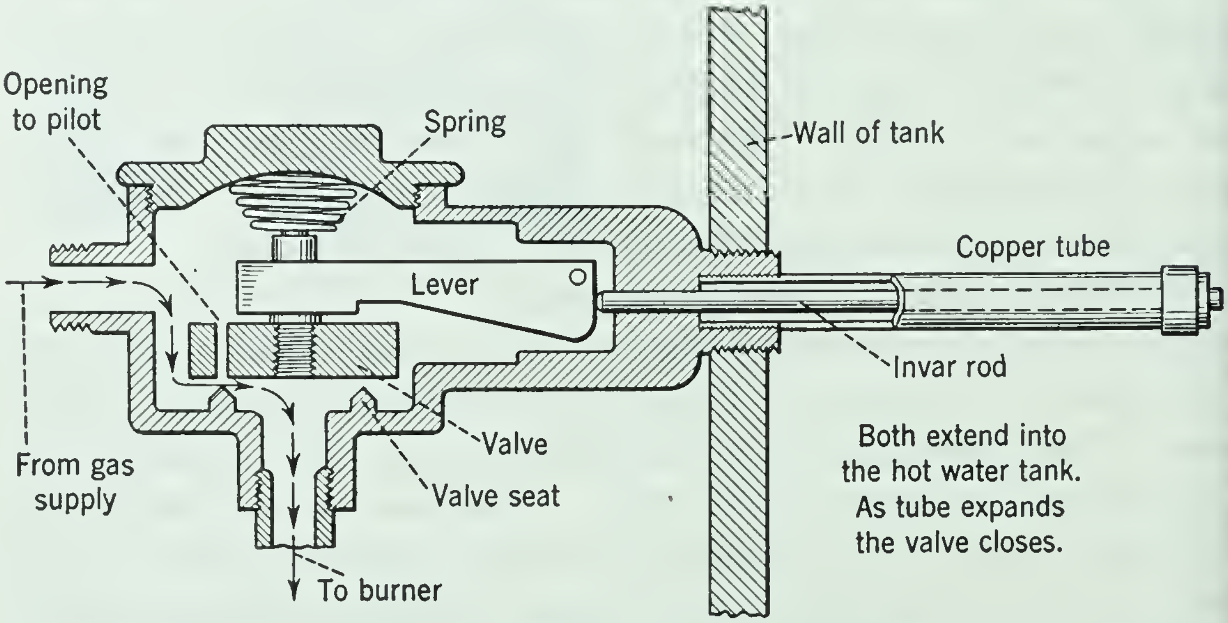


Fig. 9–4. The thermostat is used to keep water temperature constant.

How do engineers cope with the expansion problem? One manufacturer of wire fence for the farm uses spring steel, and the wires are somewhat wavy instead of straight. If the metal beams used to support a long bridge were firmly fastened to each pier, the expansion and contraction would destroy the piers. Figure 9–5 shows how engineers fasten one end of a bridge and mount the other end on rollers to permit it to expand and contract.

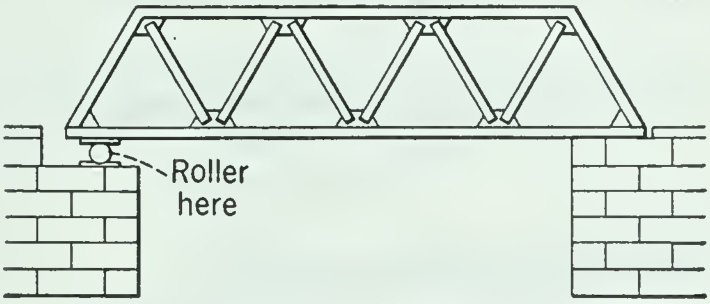


FIG. 9–5. Bridge expands when heated. Rollers permit one end to move.

Concrete blocks for roads and sidewalks have expansion joints, which may be filled with bitumen, a material that is somewhat plastic. The floor openings around the steampipes are large enough to allow the steampipes to expand and contract without lifting the floor. The manufacturers of "Pyrex" glass learned how to make a product with a very low coefficient of expansion, thus reducing the danger of breakage from heat. This glass finds extensive use in chemical laboratories, and thick glass baking dishes made of "Pyrex" glass can be put into a hot oven with little danger of breaking. The coefficient of expansion of "Pyrex" is only about one-third that of ordinary glass.

The two wires that lead in to the filament in an electric-light bulb must be sealed in the glass so perfectly that no gases can get into the bulb or escape from it. Hence they must have the same

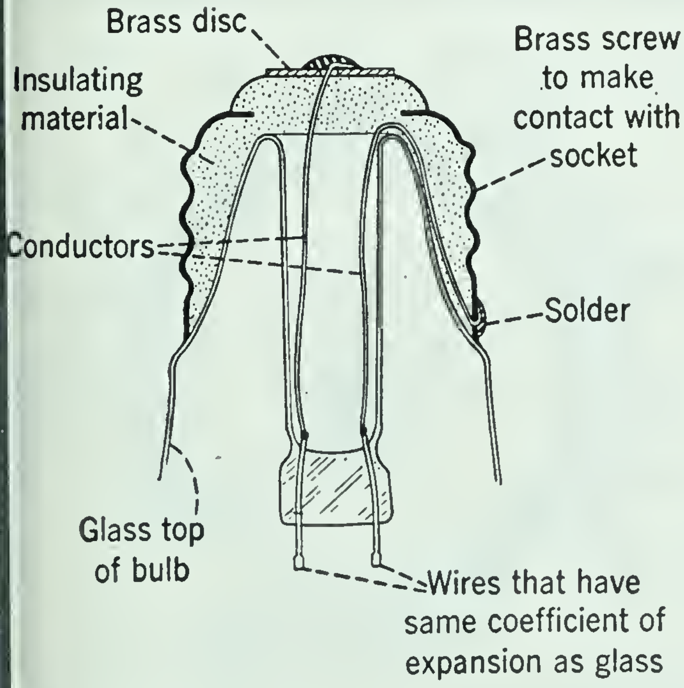

Brass disc
Insulating material
Brass screw to make contact with socket
Conductors
Solder
Glass top of bulb
Wires that have same coefficient of expansion as glass

FIG. 9–6. The lead-in wires have the same coefficient of expansion as glass.

coefficient of expansion as glass, or unequal expansion and contraction will break the seal. For a long time platinum was the only metal known which had the same coefficient of expansion as glass. Research engineers attacked the problem and developed an alloy which can be used instead of the expensive platinum. An alloy of nickel and iron, sheathed in copper is now used for the lead-in wires of electric-light bulbs. (See Fig. 9–6.)

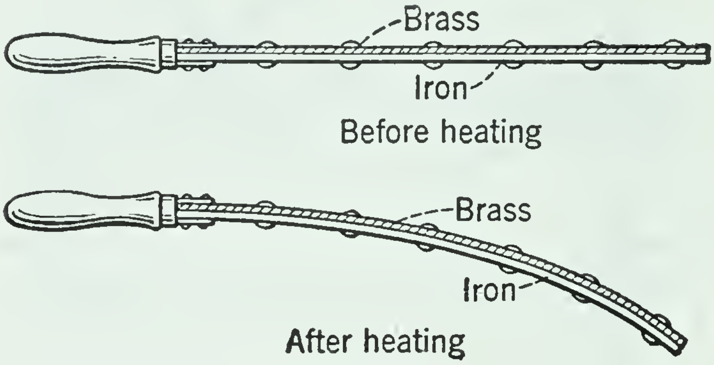
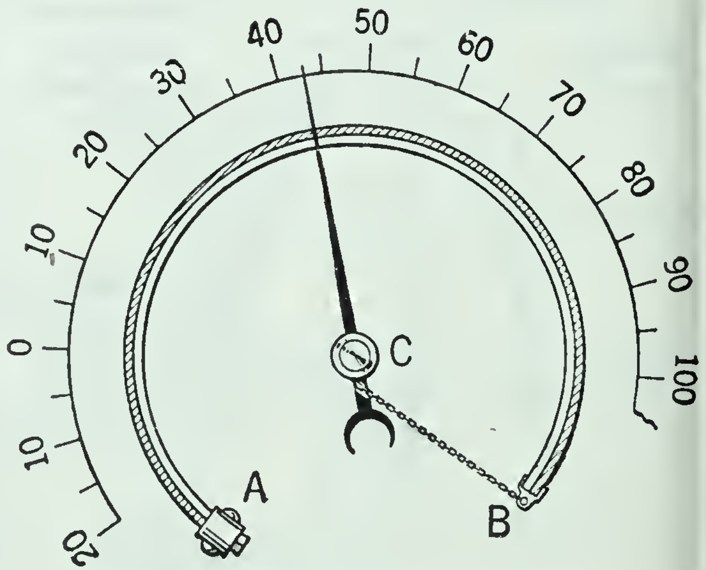


Fig. 9–7. The compound bar.

What is the compound bar? Suppose that we have two flat strips of brass and iron riveted firmly together to make a *compound bar*, as shown in Figure 9–7. If they are straight before heating, they will curve when heated, because the brass expands more than the iron does. The compound bar will straighten out again when cooled, and it will even bend in the other direction if it is cooled greatly. Of course, such a compound bar may be made by riveting or soldering together any two metals that have different coefficients of expansion.

Demonstration. Place a compound bar in the flame of a Bunsen burner. Note the direction in which the bar bends. Which of the two metals, outside or inside, has the higher coefficient of expansion?

For what purposes are compound bars used? (1) *Metallic thermometers.* From Figure 9–8, we see that one end *A* of a circular compound bar is attached firmly to the base of



Compound bar bends inward when heated

Fig. 9–8. This metal thermometer is a compound bar.

the thermometer. The end B is fastened to a pointer which is pivoted so that it can rotate about the axis C. The metal on the outside of the compound bar has the greater coefficient of expansion. When heated, it expands more and pushes the pointer in a clockwise direction along the scale. Many oven thermometers are of this type.

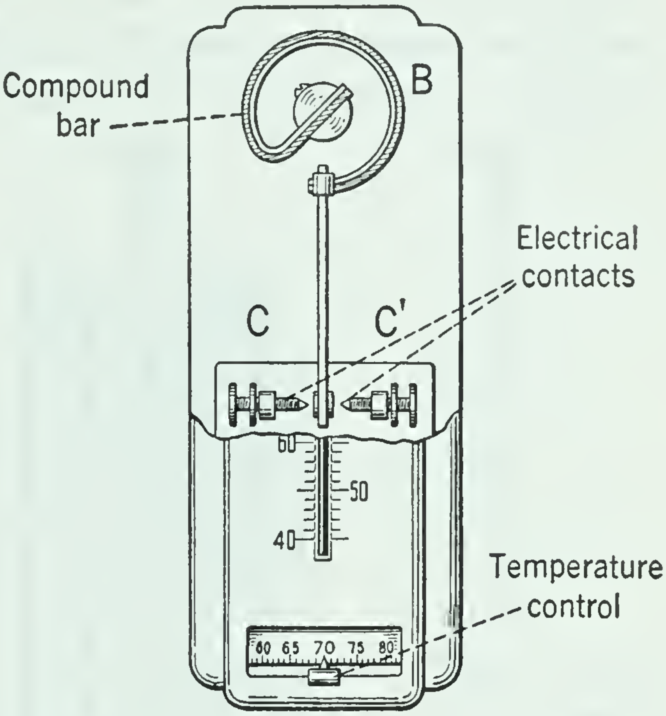


FIG. 9–9. A thermostat is designed to keep the temperature constant.

(2) *The thermostat.* To keep a room at a nearly constant temperature, a *thermostat* (temperature stationary) is often used. From Figure 9–9 we see that it operates by means of a compound bar much as the metallic thermometer does. One end of the bar is fixed. The other end is fastened to a pointer which moves back and forth between the points C and C'. If the room grows too warm, the pointer makes an electrical contact at C, and the drafts of the furnace are automatically closed. They are opened again when the room cools down enough for the pointer to make another electrical contact at C'. In this way, the temperature of a room may be kept at 68° F., for example, within a variation of one or two degrees.

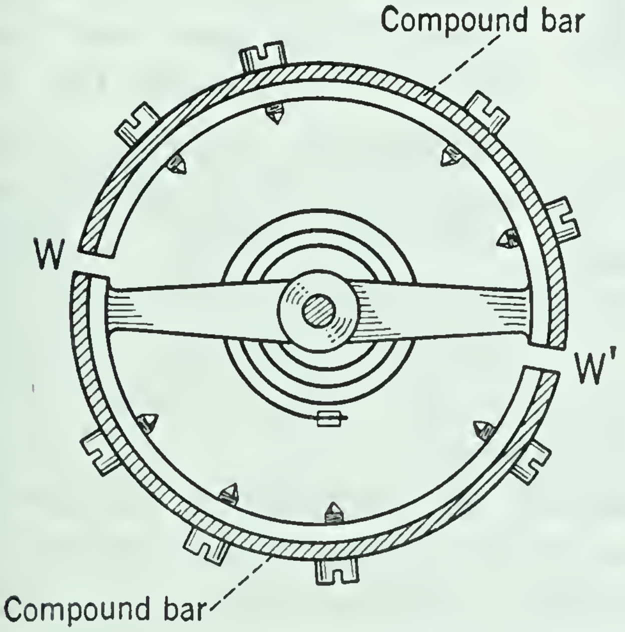


FIG. 9–10. A compensated balance wheel.

(3) *The balance wheel.* When the balance wheel of a watch expands in summer, the watch

runs too slowly. The higher priced watches have *compensated* balance wheels. As the radius of such a wheel, Figure 9–10, expands and tends to slow up the movement, the compound bars bend and throw the ends *W* and *W′* inward just far enough to accelerate the motion. It is possible to adjust such a balance wheel so that the effect of lengthening the radii is just nullified by the inward movement of the loaded ends of the bars. Such a watch is not affected by temperature changes.

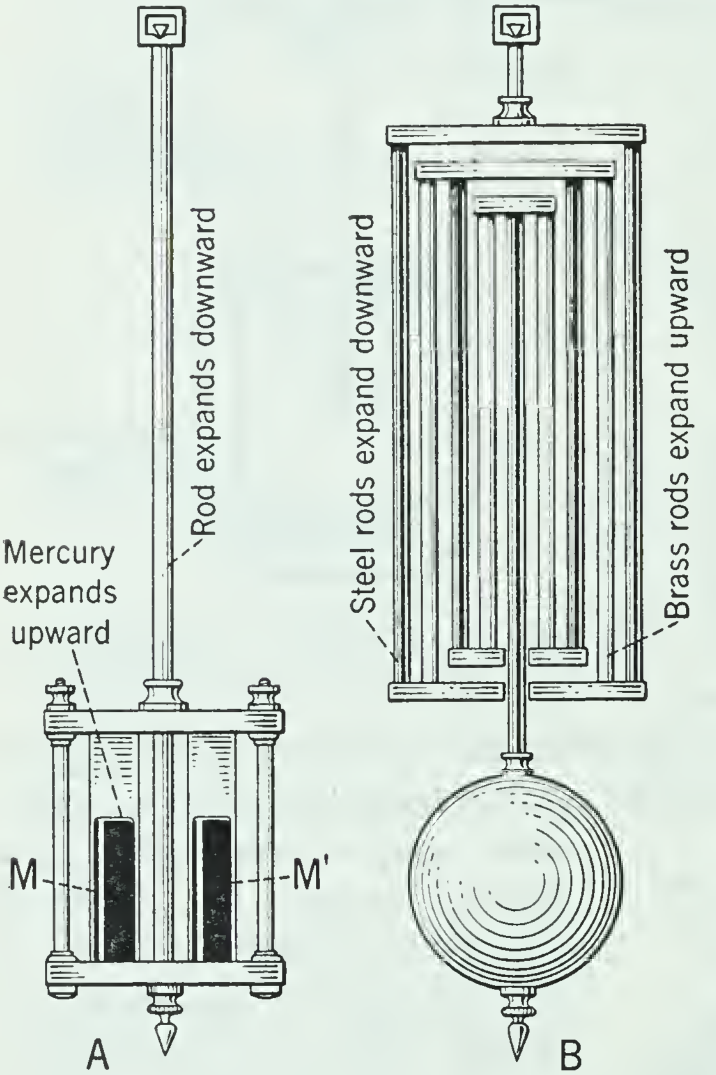


Fig. 9–11. Two types of compensated pendulums. *A*. Mercury. *B*. Bars of iron and brass.

How is elinvar used? Dr. Guillaume, who developed *elinvar*, was awarded the Nobel prize for his accomplishment. At least one manufacturer of high-grade watches uses the steel alloy known as elinvar for making hairsprings and balance wheels. Its coefficient of expansion is so low that no compound bar is needed. It seems to be superior to bimetals for use in balance wheels. It does not corrode easily and it does not become permanently magnetized. The elasticity of this alloy remains practically constant under temperature changes.

How is a pendulum compensated for temperature changes? From our study of the pendulum, we know that a long pendulum vibrates more slowly than a short one. For that reason, when the rod that supports the pendulum bob of an inexpensive clock contracts in winter the clock gains time. As it expands in summer the clock loses time. Invar is a metal used for the pendulum rods of some clocks, but *very accurate* clocks have compensated pendulums. Two types are in use:

(1) *Mercury type.* The length of a pendulum is measured from the point of suspension to the center of oscillation. The lengthening of the rod of the mercury pendulum shown in Figure 9–11*A* lowers the center of oscillation and tends to slow down the vibration rate. But the mercury at the same time expands upward and raises the center of oscillation by exactly the same amount that it was lowered by the expansion of the rod. Such a pendulum keeps accurate time, since temperature changes do not affect it.

(2) *Compensating rod type.* In the pendulum of Figure 9–11*B* the light-colored rods are of brass and the dark-colored rods are of steel. The brass rods are slightly shorter than the steel, but brass has a greater coefficient of expansion. You will observe that the expansion of the steel rods tends to increase the length of the pendulum since they expand downward. But the expansion of the brass rods tends to raise the center of oscillation, since such expansion is upward. If the rods are of the correct proportional lengths, the expansion of one set of rods nullifies the effect of the expansion of the other.

B. LIQUIDS

Examples of expansion of liquids when heated. If you fill a tank with gasoline on a cool evening, and then let it stand in the sun the next day, some of the gasoline will overflow. Heat causes liquids to expand. When the housewife cans fruit, or bottles grape juice, she fills the container full of the hot juices. Then the container is sealed. When it has cooled to room temperature, the liquid contracts until it no longer fills the container.

1. COEFFICIENT OF EXPANSION

An apparatus similar to that shown in Figure 9–12 is used to measure the coefficient of expansion of liquids. With liquids, we are not concerned with anything but their increase in volume. We measure their coefficient of *cubical* expansion, which is approximately *three times the coefficient of linear expansion.*

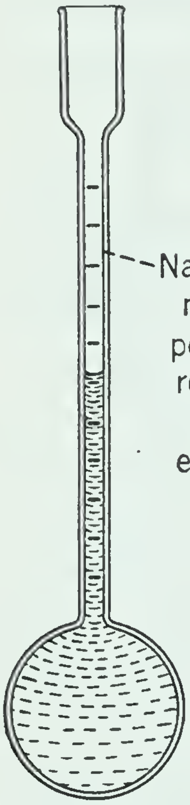

Narrow tube makes it possible to read even a slight expansion

FIG. 9–12. Tube to measure liquid expansion.

Liquids have a higher coefficient of expansion than solids. This is obvious when we compare the expansion of mercury in a thermometer with the expansion of the glass. The amount of expansion of liquids varies considerably with the temperature, but the expansion of mercury is fairly uniform between 0° C. and 100° C. Otherwise the degrees on a thermometer would be unequally spaced.

The coefficient of cubical expansion of mercury is 0.00018, nearly seven times that of glass; of water, from 5° C. to 8° C., 0.00002; of water, 99° C. to 100° C., 0.00076; of alcohol, 0.0011; and of petroleum, 0.0009.

PROBLEM. 100 gallons of petroleum are measured at 0° C. What will be the volume of the petroleum at 30° C.?

Solution. $0.0009 \times 30 = 0.027$ gal., the expansion of 1 gallon when heated 30 degrees. $0.027 \times 100 = 2.7$ gals., total expansion. $100 + 2.7 = 102.7$ gals., the new volume.

DEMONSTRATION. Fill a 250 cc. flask with colored water. Insert a one-hole stopper fitted with glass tubing one foot long. Press the stopper in until the water rises in the tube above the stopper. Place the flask over a Bunsen-burner flame and note the change in the level of the water. Does this represent linear or volume expansion of water?

2. IRREGULAR EXPANSION OF WATER

What is peculiar about the expansion of water? If we fill a flask like that of Figure 9–12 with water at 100° C., we shall find that it gradually contracts as it cools until a *temperature of 4° C. is reached.* Then it will expand again as we cool it on down to the freezing point, 0° C. Of course, when a substance contracts, its density is increased, because its mass is always constant. Therefore, *water has its greatest specific weight, which is 1.00000, at a temperature of 4° C.* At 0° C. its specific weight is 0.99987; at 20° C., its specific weight is 0.99825. See Table 10 in Appendix A.

We can find the *specific volume* of a body by dividing *one* by its specific weight. In the metric system the specific volume is that particular volume of the body in cubic centimeters that is needed to weigh one gram. The *unusual* way in which water expands when heated or contracts when cooled is clearly shown by a curve like that of Figure 9–13. The vertical axis of this graph is used for the specific volumes of water and the horizontal axis is used for the temperatures.

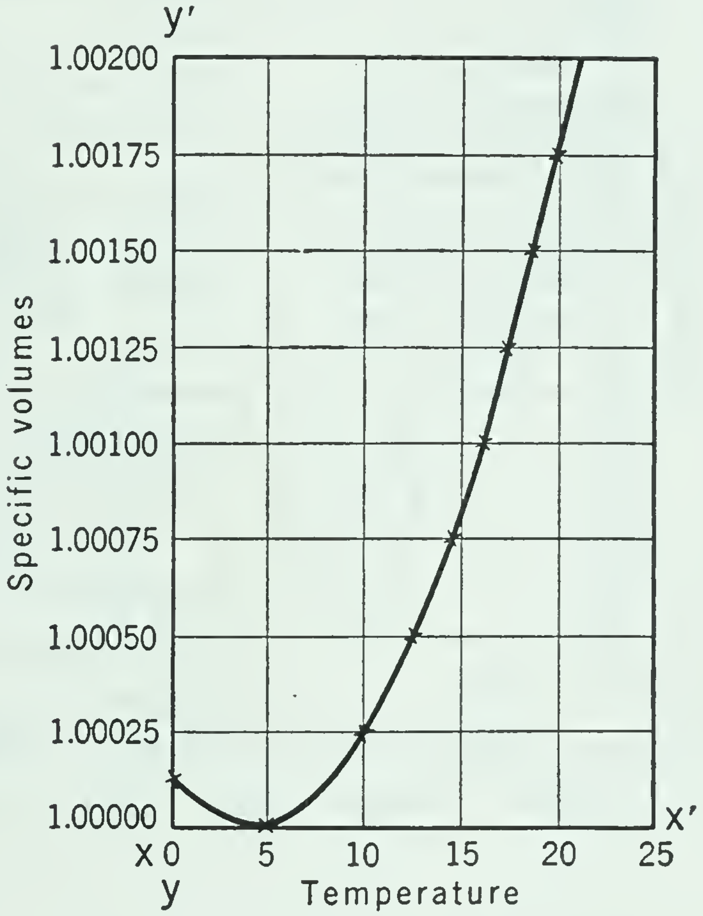


Fig. 9–13. Expansion curve of water.

If water continued to contract upon cooling until the freezing point were reached and did not expand upon freezing, ice would sink to the bottom of a pond or stream. During a long, cold winter such formation of ice would continue until the pond or stream was frozen solid. If the ice were at the bottom, it would thaw only a few feet in summer. Fish and other forms of aquatic life would perish, and many streams in the temperate zones would be closed to navigation. As it is, no ice is formed at the surface until all the water in the pond is cooled to 4° C. The water at the bottom of a frozen pond is always 4° C., whether the temperature above the ice is 20° C. or − 40° C.

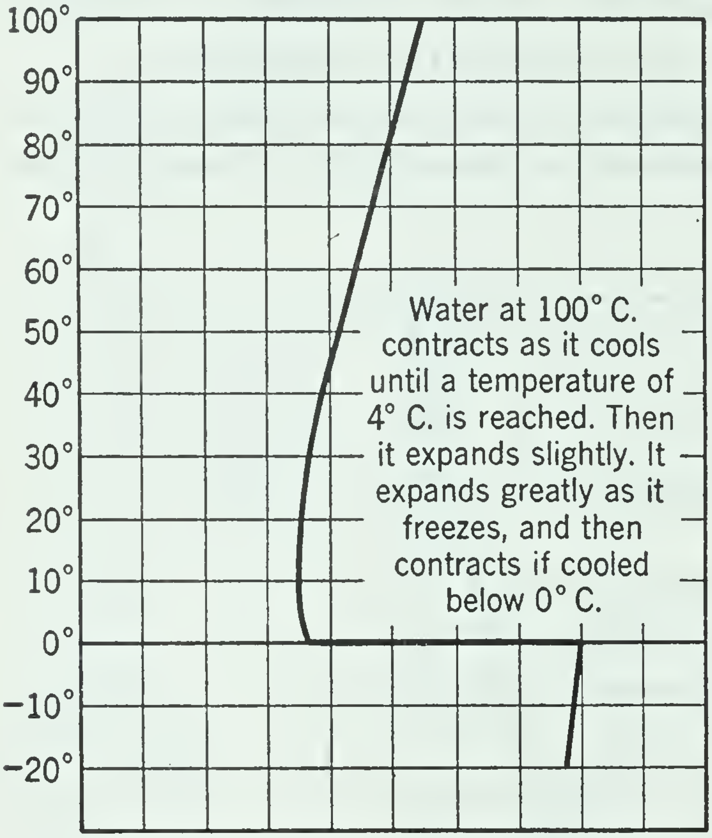


Fig. 9–14. Curve to show how water contracts when cooled.

Let us refer to Figure 9–14. The graph in this figure shows how a given volume of water *contracts* upon cooling from 100° C. to 4° C., *expands* upon cooling from 4° C. to 0° C., *expands* sharply upon freezing, and then *contracts* again when the ice is cooled below 0° C.

3. THERMOMETERS AND OTHER APPLICATIONS

How does the air thermometer work? Once again we meet the famous Galileo. This time we find that he is the inventor of the air thermometer. It consists of a glass bulb with a long tube attached. The tube dips into some colored liquid, as shown in Figure 9–15. When the bulb is warmed, the air inside the bulb expands and some of it escapes. As the air in the bulb cools, some of the liquid rises in the tube. Such a thermometer is very sensitive to temperature changes, but of course it has to be corrected each time for changes in air pressure.

How is the mercury thermometer made? To construct a mercury thermometer, a bulb is blown at one end of a thick-walled capillary tube. (See Fig. 9–16.) The bulb and part of the stem are then filled with mercury. The bulb is heated until the mercury expands and fills the tube, which is sealed at A. All the air is thus expelled from the tube. The mercury contracts on cooling and is then free to expand or contract with changing temperatures. Graduating the tube makes a finished thermometer. The mercury thermometer is not so sensitive as the air thermometer, but it is not affected by changes in pressure.

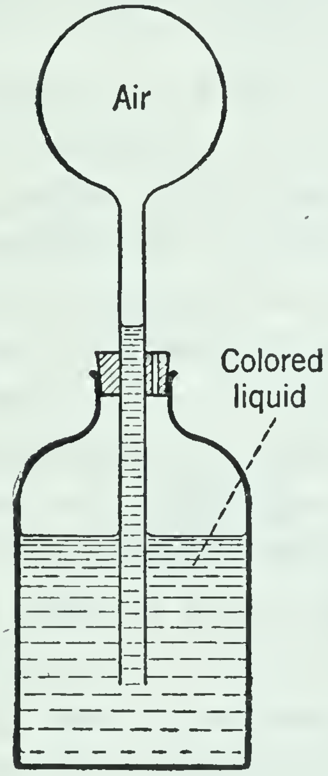


Fig. 9–15. The air thermometer was one of Galileo's inventions.

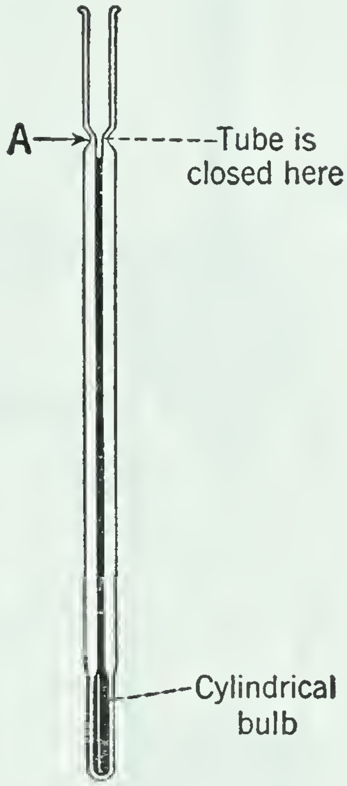


Fig. 9–16. A small-bore tube used for making a mercurial thermometer.

How do we graduate a thermometer? Before we can graduate a thermometer, some fixed points or definite temperatures must be selected. The *freezing point* and the *boiling point* of water are *two fixed temperatures* which can be easily determined.

The bulb and lower portion of the stem of the thermometer constructed as just described are packed in a funnel containing melting ice. It is more convenient to use melting ice than freezing water, and *both have the same temperature.* The lowest point to which the mercury falls is marked the *freezing point.* Such a fixed point may be etched on the glass of the thermometer tube, or upon some scale to which the thermometer is firmly attached. (See Fig. 9–17.)

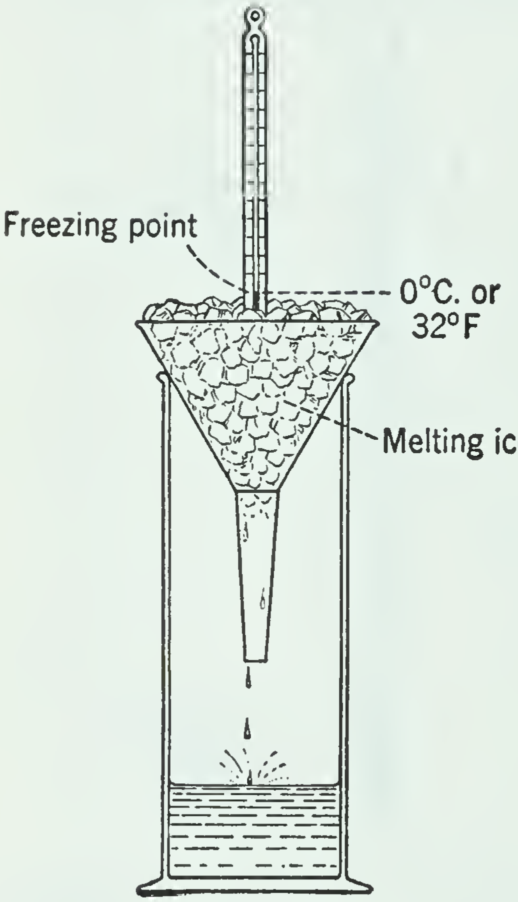


Fig. 9–17. Checking a thermometer for freezing point.

To find the *boiling point,* the thermometer is suspended in the steam arising from boiling water. (See Fig. 9–18.) The highest point to which the mercury rises is marked *boiling point* on the thermometer scale. One precaution must be taken. The boiling point of water varies with the pressure; hence, for this work the water must be boiling when it is under a pressure of exactly 76 cm. of mercury.

Demonstration. Check the fixed points of a Centigrade thermometer according to the following suggestions.

Finding the freezing point. Support the thermometer on the ring stand and pack the bulb and part of the stem in snow or ice as shown in Figure 9–17. The snow or ice should reach to the zero mark of the stem. After about five minutes, read and record the position of the mercury. Estimate to tenths of a degree all thermometer readings. The difference between the reading and the zero point is the freezing point error of the thermometer. If the freezing point indicated by your thermometer is too high, the correction is marked −; if the indication is too low, the correction is marked +. When the thermometer is being used, the corrections should be added algebraically to all readings near the freezing point.

Boiling point. Next put the thermometer through the rubber stopper and suspend it in the chimney of the boiler as shown in Figure 9–18. Enough of the thermometer stem should extend above the stopper so a few degrees below the boiling point are exposed to view, and the bulb should not be nearer the surface of the boiling water than one centimeter. The boiling should be continued at least 3 min. after the water has begun to boil. Read and record the temperature.

Water boils at 100° C. under a pressure of 760 mm. Since a variation of 27 mm. in the pressure causes a variation of one degree in the boiling point, 0.037° must be subtracted from 100° C. for every millimeter the barometer reads below 760. This gives the true boiling point. Read the barometer and compute the true boiling point under existing barometric conditions. The difference between the true boiling point as computed and the observed boiling point is the *error* for the thermometer near the boiling point. This error should be added algebraically just the same as the freezing-point error.

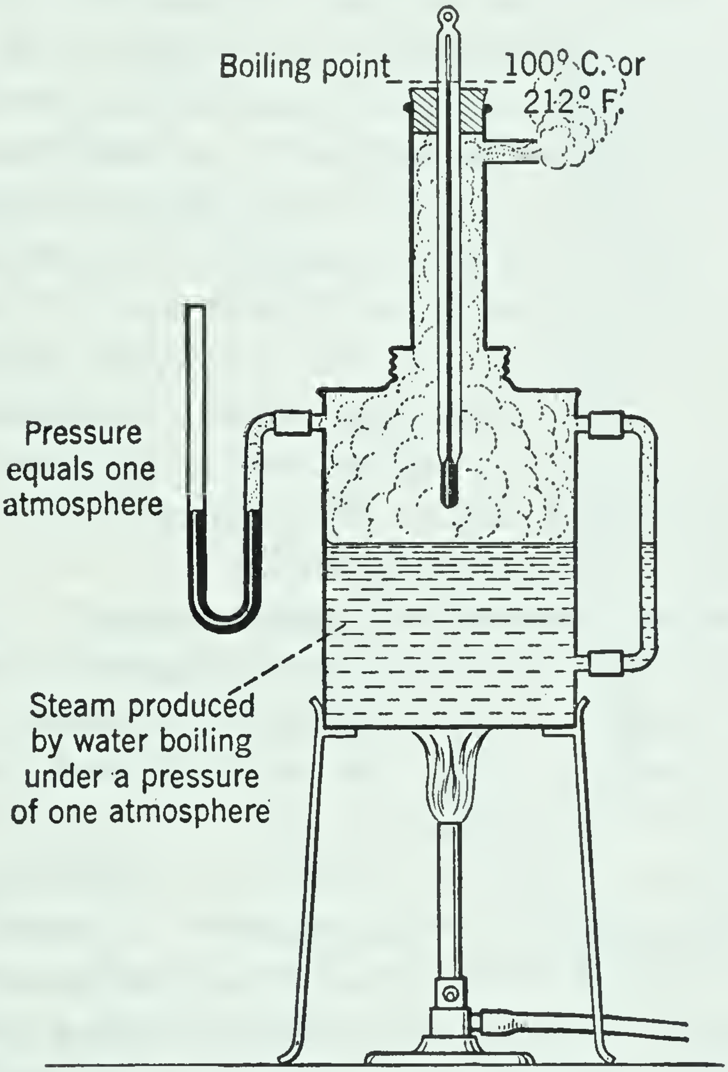


Fig. 9–18. Checking the boiling point as one fixed point of a thermometer.

Curve. Assuming that the bore of the thermometer is uniform, a curve may be plotted to show the corrections that must be made at the various points on the scale. On a sheet of cross-section paper draw a vertical line 100 spaces long. Mark the top 100 and the bottom zero; divide the line into 10 equal intervals to correspond to the 10° divisions on the thermometer. If the freezing-point correction was plus, count to the right of the vertical line opposite the zero mark one small space for each tenth of a degree correction, and indicate this position by a small plus sign. If the correction was negative, count to the left in the same manner. Do the same thing with the boiling-point correction, and join the two points thus found by a straight line. If one correction was plus and the other minus, the curve just plotted will cross the vertical line. The correction for any temperature is found by counting as tenths of a degree each small space between the curve and the vertical line at that temperature. What is the correction at 20°? What is it at 50°?

How are degrees marked on a thermometer? After the *fixed points* have been marked upon a thermometer, it must then be divided into degrees. Several scales, in which the degrees are different, have been devised, but we shall study only two, the Centigrade and the Fahrenheit.

Centigrade scale. This scale, which was devised by Celsius, is used almost exclusively in foreign countries. It is used for *scientific* work throughout the United States. On a Centigrade thermometer the freezing point is marked *zero,* and the boiling point is marked *100.* The space between the fixed points is divided into 100 equal spaces called *degrees.*

Fahrenheit scale. This scale, which was devised by Fahrenheit, is used in the United States for weather observations. On a Fahrenheit thermometer, the freezing point is marked 32 and the boiling point is marked 212. The space between these two fixed points on a Fahrenheit thermometer is divided into 180 equal degrees.

How can we convert one reading into another? Sometimes we must change meters to yards, or inches to centimeters. In a similar manner, it is sometimes necessary to change Fahrenheit thermometer readings into Centigrade readings, or vice versa. To do so, it is necessary to start with the fact that 0° C. and 32° F. are really the same temperature, and that 100° C. is the same as 212° F. Between the boiling point and the freezing point on a Centigrade thermometer we have 100 degrees and between the same points on a Fahrenheit thermometer we have 180 degrees. Therefore 100 Centigrade degrees equal 180 Fahrenheit degrees. Whence, 1 Centigrade degree equals 1.8 Fahrenheit degrees. (See Fig. 9–19.)

If a Centigrade thermometer reads 20°, the temperature is 20 Centigrade degrees above the freezing point. But it is also 36 (20 × 1.8) Fahrenheit degrees above the freezing point. If it is 36 Fahrenheit degrees above the freezing point, which is 32° F., then the Fahrenheit thermometer must read 68° when the Centigrade thermometer reads 20°. In general, then:

To change Centigrade readings to Fahrenheit readings, we multiply the Centigrade readings by 1.8, and add 32. Conversely, *to change Fahrenheit readings to Centigrade readings, subtract 32 from the Fahrenheit reading and divide by 1.8.* The following short cut may be used: To change Centigrade readings to Fahrenheit, add 40 to the Centigrade reading, *multiply* the sum by 1.8 and subtract 40. To change Fahrenheit readings to Centigrade, add 40 to the Fahrenheit reading, *divide* the sum by 1.8, and subtract 40.

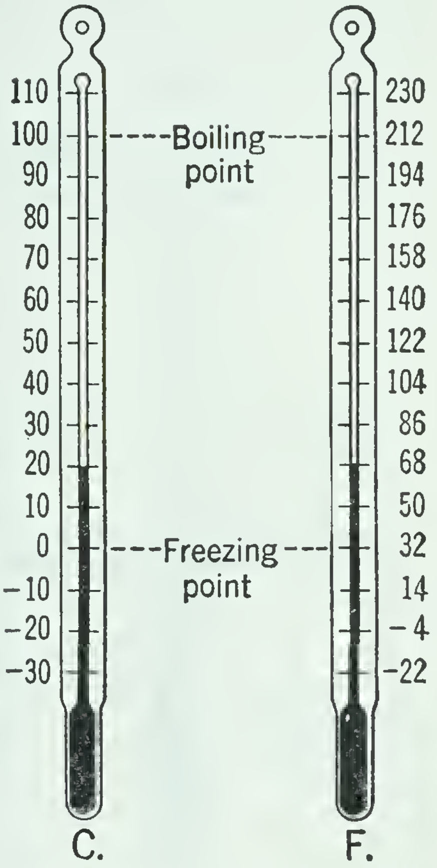


Fig. 9–19. How Fahrenheit and Centigrade thermometers compare.

Problem. Change − 10° C. to Fahrenheit. Change − 58° F. to Centigrade.

Solution. − 10 × 1.8 = − 18; − 18 + 32 = 14. Hence, − 10° C. equals 14° F. In problem No. 2, − 58 − 32 = − 90; − 90 ÷ 1.8 = − 50° C. Therefore, − 58° F. equals − 50° C.

How is the mercury thermometer limited? Since mercury freezes at a temperature of about – 39° C., it cannot be used to measure temperatures below that point. Rear-Admiral Byrd needed an alcohol thermometer for use in the polar regions, where much lower temperatures are common. The freezing point of ordinary alcohol is – 130.5° C. It is usually colored red or blue so that it can be seen more easily.

For *very* low temperature measurements, a gas thermometer is used. (See Fig. 9–20.) The bulb contains hydrogen, which contracts upon being cooled. The mercury in the bent tube rises at *B* and falls at *C*. Then the tube is lowered until *B* drops to its former level. The temperature is calculated from the *change of pressure* needed to keep the volume of the hydrogen gas constant.

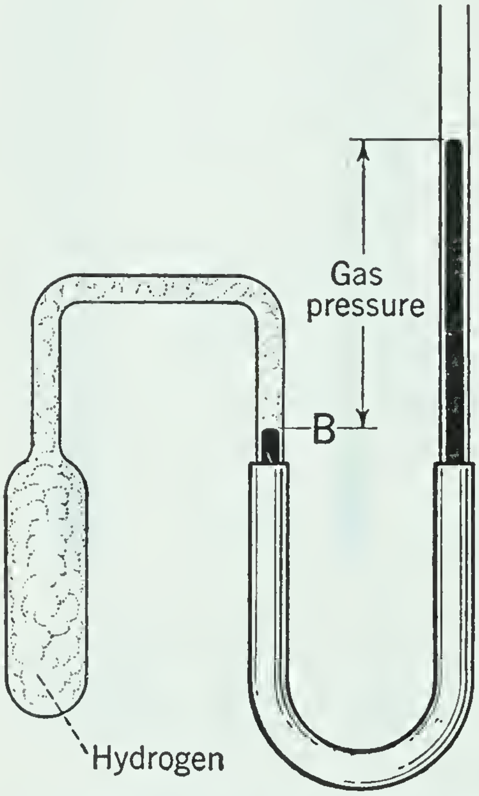


Fig. 9–20. A gas thermometer.

The boiling point of mercury is 357° C. Hence the mercury thermometer is not suitable for measuring *high* temperatures. Several methods of measuring high temperatures are in use. Sometimes a gas thermometer is used. Platinum changes its electrical resistance with the temperature, and a *platinum resistance* thermometer is used to determine temperatures by measuring the amount its resistance changes. Two metals in contact will produce electricity when heated. Temperatures are sometimes determined by measuring the amount of electricity such a *thermocouple* produces.

There are special thermometers for special uses. (1) *Clinical.* The thermometer used by physicians for taking the temperature of the human body needs only a short scale, because our normal temperature is 98.6° F., and it never varies more than a few degrees in either direction. Since the scale of the *clinical* thermometer is usually graduated from 92° F. to 110° F., it is possible to have the degrees far enough apart so that the scale can be read when divided into *tenths* of a degree.

In still another way the clinical thermometer is different. The tube is *constricted* to reduce the size of the bore just above the cylindrical bulb. The mercury forces its way past this constriction as it expands, but the cohesion of the mercury molecules is not great enough to pull the mercury column back past the constriction. Hence the top of the mercury column remains at the highest reading, which can be read at leisure. The thermometer is then given several quick jerks to shake the mercury back into the bulb to be ready for the next reading. (See Fig. 9–21.)

(2) *Maximum thermometers.* Such thermometers are used by the Weather Bureau to show the highest temperature within a given time, usually 24 hours. One type of maximum thermometer is constructed like the clinical thermometer. It is set at a certain hour each day by shaking the mercury down into the bulb. Then as the temperature increases, the mercury rises in the tube and stands at the highest temperature reached during the day. In another type, the mercury pushes a little steel index upward as it rises. The friction of this index against the inner walls of the tube holds it at the highest recorded temperature. To set the thermometer for a subsequent reading a magnet is used to drag the steel index down into contact with the mercury.

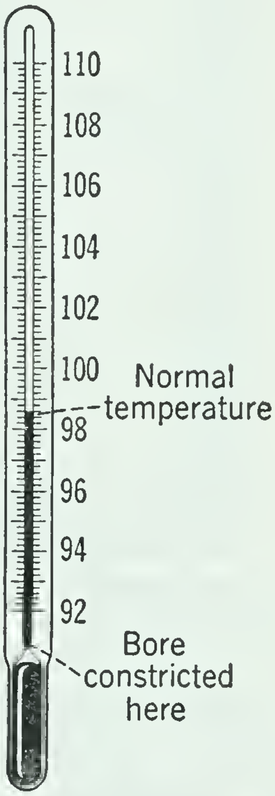


Fig. 9–21. The clinical thermometer.

(3) *Minimum thermometer.* The bulb of one type of *minimum* thermometer is filled with alcohol. The surface tension of the alcohol drags a small steel index along the tube as the alcohol contracts. This index is left at the lowest temperature reading for the time interval, because the alcohol flows past it when it

expands again. (See Fig. 9–22.) This thermometer, too, is set by the use of a magnet.

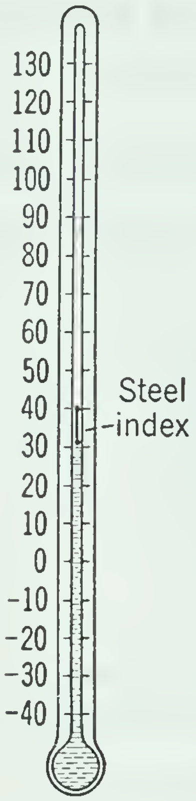


Fig. 9–22. A minimum thermometer.

(4) *Maximum-and-minimum thermometer.* By the use of bent tubes like those shown in Figure 9–23, both the maximum and minimum temperatures can be read from the same instrument. One bulb contains alcohol and alcohol vapor. Since the alcohol vapor is easily compressible, the tube is not broken as the mercury column in the bent tube is pushed backward and forward.

(5) *Self-registering instruments.* The thermometer of Figure 9–24 is a metal type which carries an ink pointer to record the temperature on a graph, which consists of a sheet of ruled paper wound on a cylinder. A clockwork mechanism turns the cylinder through one complete revolution per week, while the pointer traces a continuous line which shows the temperature at any particular day or hour of the week. (See Figs. 9–25 and 9–26.)

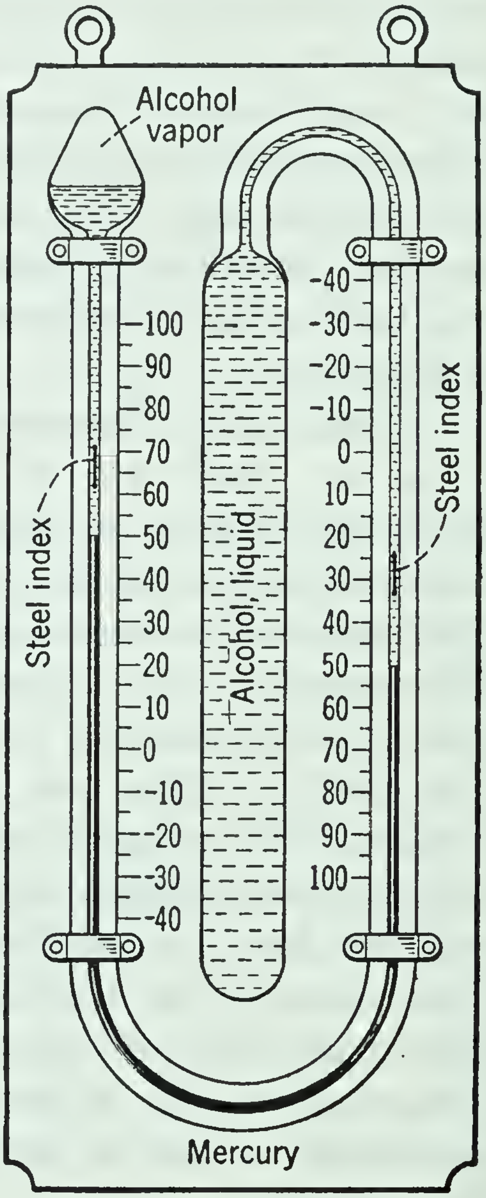


Fig. 9–23. A maximum-and-minimum thermometer.

Expansion of liquids in closed containers. In hot-water heating systems, allowance must be made for the expansion of water when heated. That is the reason for expansion tanks. Whenever liquids (gasoline, for example) are stored in closed tanks or containers, allowance must be made for the expansion and contraction which temperature changes will cause.

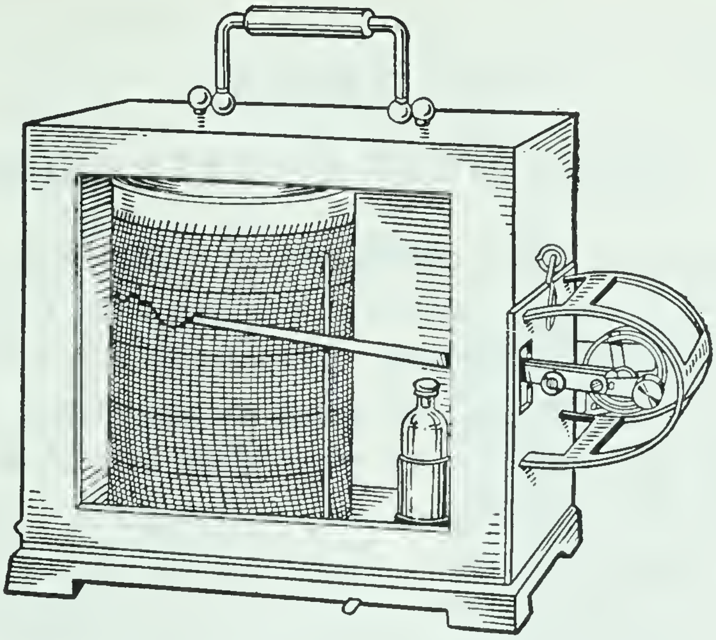


FIG. 9–24. A thermograph, or self-recording thermometer.

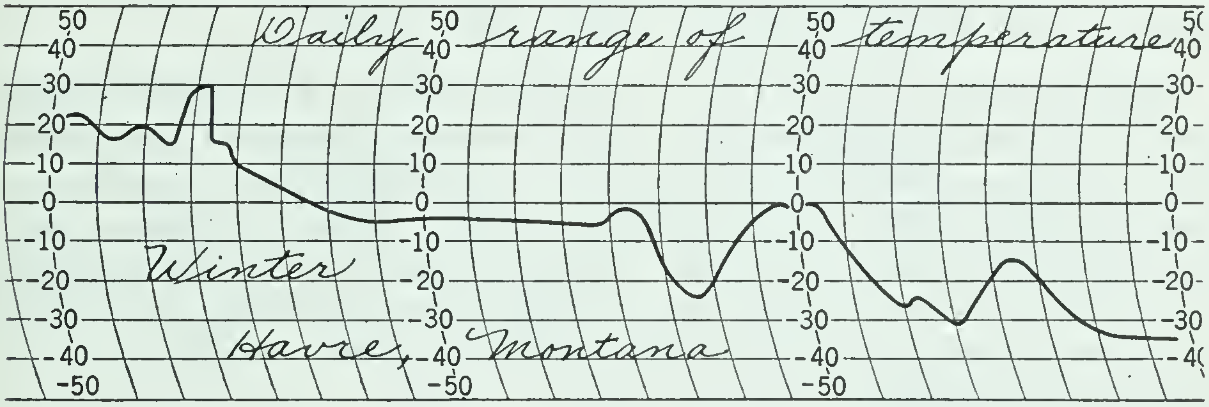


FIG. 9–25. The graph shows a decided cold wave during a week in January at Havre, Montana.

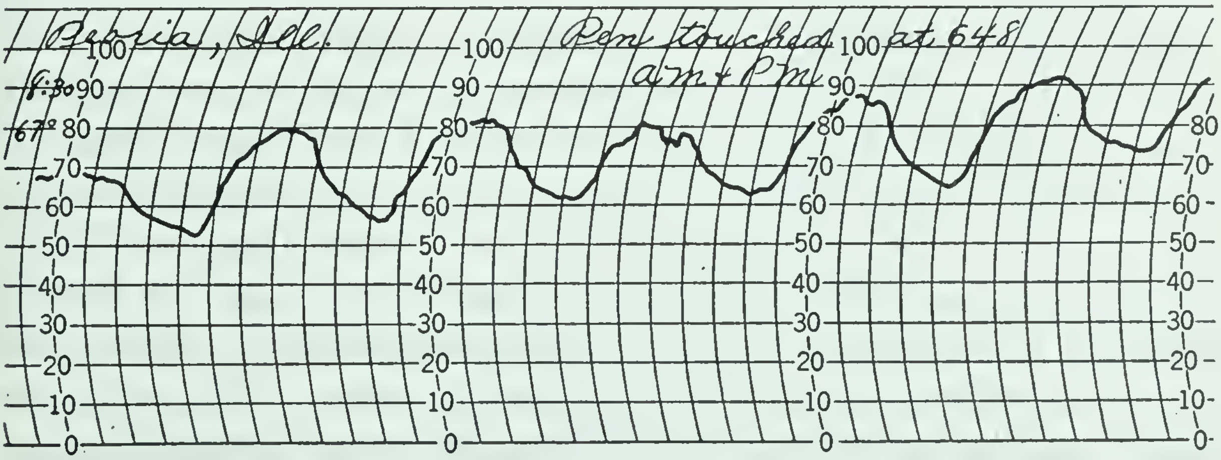


FIG. 9–26. The graph shows daily variations in temperature at Peoria, Illinois.

C. GASES

1. COEFFICIENT OF EXPANSION

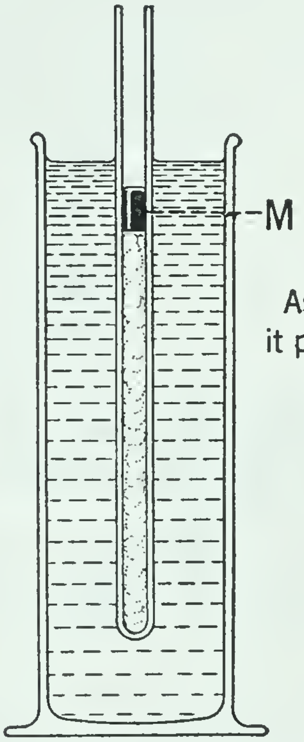
All gases have the same coefficient of expansion. When bread or biscuit dough is put in the oven, the gas used for leavening expands greatly during the heating. This expansion makes the dough rise. Experiment shows that all gases expand when heated.

Unlike solids and liquids, *all gases have the same coefficient of expansion,* and *it is uniform at all temperatures.* With gases we are concerned *only* with the cubical coefficient of expansion, or their increase in volume. The value of the coefficient of cubical expansion per degree Centigrade for all gases is $\frac{1}{273}$ or 0.003665 of the volume at 0° C. It is about 20 times as great as that of mercury and almost 60 times that of aluminum.

Demonstration. Insert into a Florence flask a one-hole stopper fitted with glass tubing one foot long. Invert the flask and dip the end of the tube into a beaker of water. Warm the flask by moving a Bunsen flame across it. Why do air bubbles escape? Allow the flask to cool. Note the rise of water in the tube. See if the heat of your hand will affect the height of the water in the tube. Is this change in water level due to linear or volume expansion of air? Which has the greater rate of expansion, air or water?

2. CHARLES' LAW

How is the coefficient of expansion of gases measured? In 1787, Charles, a Frenchman, performed experiments proving that all gases expand the same amount when heated one degree, if the pressure is kept constant. Suppose we take a small glass tube, sealed at one end, and measure the air column enclosed by a globule of mercury M, as shown in Figure 9–27, when the tube is immersed in ice water. Next we may measure the length of the air column when the tube is immersed in steam. We find that the air column has increased in length $\frac{100}{273}$ of its original length, when heated from 0° C. to 100° C. For each degree of temperature change, the expansion is $\frac{1}{273}$ of the volume at 0° C. When other gases are used, the same result is obtained. While Charles was the first to study the expansion of gases, the law sometimes bears the name of Gay-Lussac, who was the first to announce the law showing the relation of the volumes of gases to their temperatures.



As gas expands it pushes mercury globule up the tube

Fig. 9–27. Tube to measure the coefficient of expansion of gases.

3. ABSOLUTE ZERO

What is meant by absolute temperature? Since gases contract when cooled, it is interesting to inquire what will happen as we continue to cool them below 0° C. Let us start with *unit* volume at 0° C. But unit volume is really $\frac{273}{273}$. For every degree we cool the gas below zero, its volume will be decreased $\frac{1}{273}$. At − 100° C. it is decreased by $\frac{100}{273}$, and only $\frac{173}{273}$ of its original volume will be left. At − 200° C., only $\frac{73}{273}$ will be left. How much will remain if we cool the gas to − 273° C.? Theoretically, it will have *lost all its volume.* At *zero volume* all molecular motion would cease and the body would be without any heat, or *absolutely* cold. For this reason, − 273° C. is taken as zero on the *absolute temperature scale* devised by Lord Kelvin. Thermometers are never graduated on the absolute scale and it is not used for measuring temperatures. It is merely an arbitrary scale which was devised to eliminate the *zero* and the *minus* from regular thermometer scales when comparing gas volumes.

In reality, all gases liquefy before absolute zero is reached. One scientist after another has attempted to cool some gas to absolute zero. One of the best known cryogenic laboratories is at Leyden, Holland, where Kamerlingh Onnes liquefied helium in 1908. De Haas, working in this laboratory, succeeded in reach-ing a temperature within 0.003 of a Centigrade degree of absolute zero. The table given below shows the relation between the absolute and Centigrade scales, and the relation of the absolute scale to the volume of a gas which measures 273 cc. at 0° C.

Centigrade	Absolute	Volume
100°	373°	373 cc.
50°	323°	323 cc.
0°	273°	273 cc.
−100°	173°	173 cc.
−273°	0°	0 cc.

By comparing columns one and two we see that the absolute temperature is exactly 273 degrees higher than the Centigrade temperature. Hence, to change from Centigrade to absolute scale, we add 273 degrees to the Centigrade reading. The third column shows how 273 cc. of gas at standard temperature, 0° C., would behave if subjected to the temperatures shown in the other columns. At 100° C., or 373° A., its volume is 273 cc.; at − 100° C., or 173° A., its volume is 173 cc. From these observations, it is apparent that the LAW OF CHARLES may be stated as follows: *If the pressure be constant, the volume of a given mass of dry gas is directly proportional to the absolute temperature.*

PROBLEM. At a temperature of − 23° C., the volume of a gas measures 1000 cc. Find its volume at a temperature of 27° C.

Solution. − 23° C. = 250° A., and 27° C. = 300° A. The gas has been warmed; hence it will expand to $\frac{300}{250}$ of its former volume. $\frac{300}{250} \times 1000 = 1200$ cc., the new volume.

4. GRAPHIC REPRESENTATION OF CHARLES' LAW

How to make the graph. Let us use the absolute temperatures and volumes given in the preceding section as co-ordinates in plotting a curve. The curve obtained is shown in Figure 9–28. It is a simple direct-proportion curve, and it shows graphically that the volume of a gas is directly proportional to the *absolute* temperature.

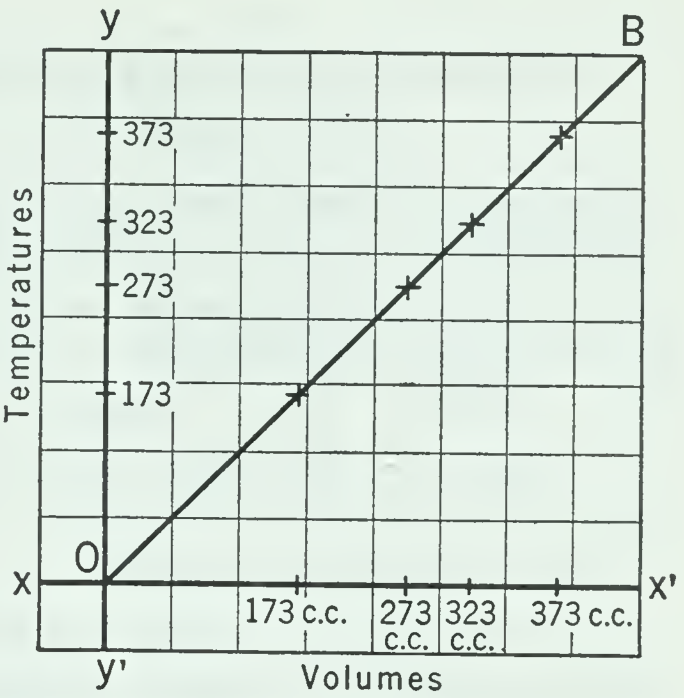


Fig. 9–28. Direct proportion curve to represent the law of Charles.

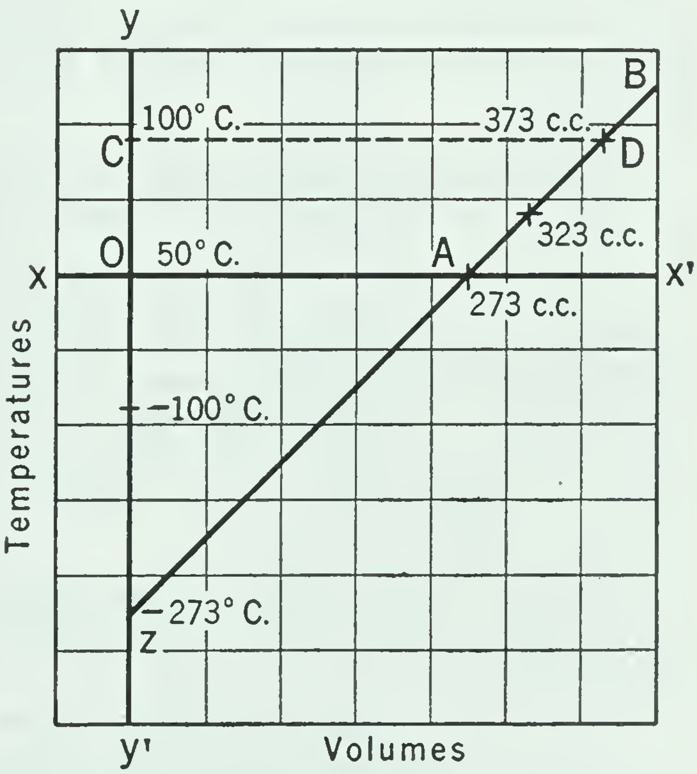


Fig. 9–29. Curve to show absolute zero.

If we plot a curve by using the volumes as abscissas and the *Centigrade* temperatures as ordinates, as shown in the same table, we see that the volumes are *not* proportional to the Centigrade temperatures at all. If we produce the curve AB until it intersects the YY' axis at Z, we find that this point of intersection corresponds to − 273° C., or to zero degrees absolute. This furnishes us with a graphic illustration of the *theoretical* temperature at which all gases cease to have volume. In the similar triangles, ZCD and ZOA, the volumes, as represented by OA and CD, are proportional to the *absolute* temperatures, OZ and CZ. (See Fig. 9–29.)

There is no simple volume relationship corresponding to 0° C. and 10° C., or to − 10° C. and 10° C. The latter two, if used in proportion, would give a negative volume, which is not possible. The absolute scale eliminates the zero and negative temperatures of the Centigrade scale.

Absolute temperature T = Centigrade temperature $t + 273$. Or, $T = t + 273$.

5. PROBLEMS IN THE VOLUME, TEMPERATURE, AND PRESSURE OF GASES

Problems involving the use of the law of Charles. Suppose we have 400 cc. of gas measured at 10° C. and wish to find what volume the gas will occupy at 60° C. We must first reduce the Centigrade temperatures to absolute. 10° C. = 283° A. and 60° C. = 333° A. Let V represent the original volume; V', the new volume; T, the original temperature; and T', the new temperature.

Then by the law of Charles,

$$V : V' = T : T'$$

Substituting, $400 : x = 283 : 333$

$$x = 470.6 \text{ cc.}$$

It is quite as simple to solve by fractions. The temperature has increased and the volume will be correspondingly increased. Hence the new volume is $\frac{333}{283}$ of the original volume. $\frac{333}{283} \times 400 = 470.6$ cc.

Problems involving the use of the laws of Boyle and Charles. It frequently happens that both the temperature and pressure to which a given volume of gas is subjected may change. To find the new volume in such a case, we must use the laws of Charles and Boyle. We may find the effect of the pressure on the volume and then use this new volume in order to find the effect of temperature. Or we may find the effect of both by the use of a single statement.

Problem. Given 500 cc. of gas at 20° C. and 750 mm. pressure; find what volume the gas will occupy at 30° C. and 760 mm. pressure.

Solution.

$$20° \text{ C.} = 293° \text{ A.}; \ 30° \text{ C.} = 303° \text{ A.}$$

Then, $500 \times \frac{303}{293}$ = the volume corrected for temperature change only.

And, $500 \times \frac{750}{760}$ = the volume corrected for pressure change only.

Since both the temperature change and the pressure change occur simultaneously, we may combine the equations as follows:

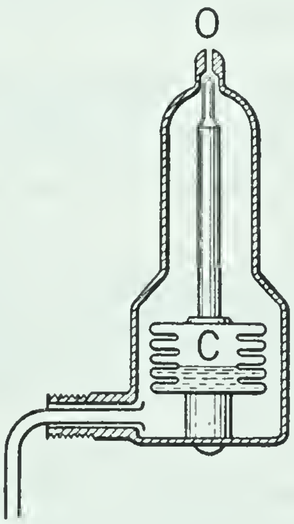
$$500 \times \frac{303}{293} \times \frac{750}{760} = \text{corrected volume}$$

NOTE. The increase in temperature from 20° C. to 30° C. causes the gas to expand by $\frac{303}{293}$ of its volume, and the increase in pressure reduces the volume by $\frac{750}{760}$.

The following formula may be used for solving problems when both the absolute temperature and pressure change: $\frac{PV}{T} = \frac{P'V'}{T'}$. In this formula P, V, and T represent the original pressure, volume, and absolute temperature respectively; P', V', and T' represent the new pressure, volume, and absolute temperature.

6. APPLICATIONS OF THE EXPANSION OF GASES

Since two things cannot occupy the same place at the same time, we cannot get any steam from the furnace into our radiators unless we make provision for the air in the radiators to get out. But we must not let the steam escape. To see how one can manage to let the air escape, but keep the steam inside, let us refer to Figure 9–30. The metal capsule C contains a liquid which changes to vapor when it is heated by steam. The vapor then exerts pressure and pushes the top of the capsule upward until the metal rod on its top closes the opening in the valve. The elasticity of the corrugated metal of which the sides of the capsule are made permits the top to move upward when the pressure inside the capsule increases, but it springs back to its former position as the vapor inside condenses again.



Liquid evaporates. Its vapor expands and closes the opening, O.

FIG. 9–30. The radiator valve.

One type of valve has been devised which permits some vapor to escape and to increase the relative humidity of the room.

SUMMARY

1. In general, solids expand when heated and contract when cooled. The increase per unit length per unit degree is called the coefficient of linear expansion. The increase in area, or the coefficient of superficial expansion, is approximately twice the linear coefficient. The increase in volume, or the coefficient of cubical expansion, is three times the linear coefficient.

2. Liquids have a much higher coefficient of expansion than solids; alcohol expands nearly 30 times as much as steel, and mercury nearly 5 times as much. Water has its maximum density at 4° C.; heated above this temperature or cooled below it, water expands.

3. The coefficient of expansion per degree Centigrade of all gases is the same, 0.003665 of its volume at 0° C.

4. A change in temperature or a change in pressure will change the volume of a gas. The GAS LAW, $\frac{VP}{T} = \frac{V'P'}{T'}$, is used to calculate the effect of temperature and pressure changes upon gas volumes.

5. Sensation is an unreliable method of determining temperature. A thermometer is an instrument devised for that purpose.

6. To change Centigrade readings to Fahrenheit, multiply the reading by 1.8 and add 32; to change Fahrenheit readings to Centigrade, subtract 32 from the Fahrenheit reading and divide by 1.8.

7. Special thermometers are constructed to show the maximum or minimum temperature for any given period, usually 24 hr.

8. The clinical thermometer is used to find the temperature of the human body. Self-registering thermometers keep a continuous record of the temperature for any given period.

How many of the following terms can you define or explain?

Expansion
Coefficient of linear expansion
Compound bar
Fahrenheit thermometer
Centigrade thermometer
Clinical thermometer
Law of Charles
Coefficient of expansion
Absolute temperature
Absolute zero

SELF-TESTING EXERCISES

Answer These Questions

On a separate sheet of paper numbered from 1 to 7 write the letters for the phrases that answer the following questions correctly.

1. What happens to solids when they are heated? (*a*) They contract; (*b*) they expand; (*c*) they remain unchanged.

2. Which of the terms correctly completes the following statement? Heating a solid, liquid, or gas does not change its (*a*) density; (*b*) volume; (*c*) weight.

3. What is the correct name for the increase in unit length of a solid per degree rise in temperature? (*a*) Specific heat; (*b*) coefficient of volume expansion; (*c*) coefficient of linear expansion.

4. Coefficient of cubical expansion of solids is slightly more than a certain number times the coefficient of linear expansion. Which of the following is the correct number? (*a*) 1; (*b*) 2; (*c*) 3.

5. Which of the following is the only degree at which water, due to its irregular expansion, has a specific weight of one? (*a*) 0° C.; (*b*) 20° C.; (*c*) 4° C.; (*d*) 100° C.

6. Which of the following figures represents the true coefficient of volume expansion for all gases? (*a*) 0.03665; (*b*) $\frac{1}{273}$; (*c*) 1; (*d*) 0.01.

7. Which of the following phrases represents the true volume of a given weight of gas if pressure is constant? (*a*) Inversely proportional to Centigrade temperature; (*b*) directly proportional to Centigrade temperature; (*c*) directly proportional to absolute temperature; (*d*) inversely proportional to absolute temperature.

Complete These Statements

On a separate sheet of paper numbered from 1 to 8 write the words needed to fill correctly the blank spaces in the following sentences.

Thermostats make use of expansion in the ..(1)... For exceptionally cold climates, the liquid used in a thermometer is ..(2)... Water boils at 100° C., provided the air pressure is ..(3)... In the use of leavening agents in baking, the law of ..(4).. is exemplified. Pyrex glass finds use in making baking dishes because it has ..(5)... Glass stoppers are sometimes hard to remove from bottles; they may be loosened by ..(6)... Theoretically the volume of a gas at absolute zero would be ..(7)... The absolute temperature scale was devised by ..(8)...

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 10 write a T *or an* F *to show whether each statement is true or false.*

1. The coefficient of expansion of aluminum is 0.000023. One foot of aluminum wire will increase 0.00023 ft. when heated 100° C.
2. One hundred feet of aluminum wire will increase 0.023 ft. when heated 10° C.
3. The alloy elinvar is used as a substitute for the compound bar for the balance wheels of some watches.
4. Brass is an alloy that is used for lead-in wires of electric light bulbs.
5. The water at the bottom of a frozen pond always has a temperature of zero degrees Centigrade.
6. Ice occupies about 1.1 times the volume of the water from which it was formed.
7. Theoretically, the lowest possible temperature is − 459° F.
8. The operation of some types of steam radiator valves depends upon the fact that most substances expand when heated.
9. Because gases expand when heated, warm air is less dense than cold air.
10. The metallic thermometer is a practical application of the compound bar.

QUESTIONS

1. How would thermometer readings be affected if mercury and glass had the same coefficient of expansion?
2. When two tumblers stick together they may usually be loosened by pouring cold water into the inner one, or by letting hot water run over the outer one. Explain.
3. Why must all the water in a pond be cooled to 4° C. before any of it freezes?
4. Why do ponds and lakes freeze around the edges before they do in the middle?
5. Fused silica has a coefficient of expansion of about 0.0000005. Explain why it is superior to glass for laboratory apparatus that is to be heated.
6. Why is glassware to be heated in the laboratory made of thin glass instead of thick glass?
7. Sometimes a housewife instructs her maid never to pour hot water into her thin glass tumblers. Is she really scientific?

8. A football is inflated in a warm room. It is used out-of-doors on a cold day. Will it grow looser or tighter? Explain.

9. Why is invar used in making clock pendulums, and the tapes used by surveyors?

10. Compare the coefficients of linear expansion of "Pyrex" glass and ordinary glass. Explain why dealers in "Pyrex" glass can guarantee to replace baking dishes made of "Pyrex" if they break when being heated.

11. Are high or low temperatures generally associated with areas of high barometric pressure? Explain.

12. How does the law of Charles apply in the baking of bread?

13. Rivets used to hold together steel plates in construction work are heated red hot before they are headed. Why?

14. Why are concrete roads marked off into blocks, and the cracks filled with tar or bitumen when building roads?

15. Would a single large sheet of copper be satisfactory to cover one half of a roof on a house? Explain.

16. Metal straps are used to support the steampipes in the basement. Explain why this method is used.

17. One hot summer day one of the drawbridges across the Passaic River could not be closed. Can you give a reason and suggest a remedy?

18. Why is it impossible to seal a brass wire into a glass rod?

19. Why is it harder for a plumber to make a tight joint with a brass hot-water pipe than with one of galvanized iron?

20. Is it better economy to have your gas meter in the basement or in the attic? What two factors must be taken into consideration in answering the foregoing question?

21. How would natural conditions be affected if water continued to contract until it froze?

22. When some of the gasoline pumps had ten-gallon glass cylinders at the top for storage, a certain motorist would never stop for gasoline at a station unless it stood in the shade. Explain.

23. A small rubber balloon filled with hot air rises. Explain.

24. The air above the ice of a pond is $-10°$ C. What temperature would you expect the upper surface of the ice to have? The lower surface? The water just beneath the surface? The water at the bottom of the pond?

25. Why does the air escaping from the valve of a pneumatic tire feel cool, even in hot weather?

26. Sometimes it is difficult to remove the glass stopper from a bottle. Why does pouring hot water over the neck of the bottle help to loosen the stopper?

27. An automobile owner neglects to oil his car. What does a mechanic mean when he speaks of a moving part as having "frozen"?

28. Why are large piles of broken rock usually found at the base of rocky cliffs?

29. What are the properties of elinvar which make it useful?

30. How does the size of the bulb of a thermometer affect its sensitiveness? What other factor affects the sensitiveness of an ordinary thermometer?

31. Why must the air thermometer be corrected for pressure changes?

32. Why must a thermometer tube be of uniform bore?

33. Should a thermometer have a spherical or a cylindrical bulb? Give a reason for your answer.

34. What properties should a liquid have to make it suitable for use in a thermometer?

35. Why does the mercury in a thermometer drop a fraction of a degree before it begins to rise when the bulb is plunged into hot water?

36. What objection is there to the use of boiling water for sterilizing a clinical thermometer after use?

37. A mother uses a clinical thermometer and finds that her little girl has a temperature of 102° F. She lays the thermometer aside and rushes to telephone the doctor. The following morning she takes her son's temperature. What will be its probable reading?

38. How should a thermometer be held while it is being read?

39. How accurate are the thermometers given away for advertising?

40. Does the mercury in a thermometer ever freeze in cold climates?

PROBLEMS

1. A steampipe is 40 ft. long at a temperature of 10° C. How much does it expand when steam at 100° C. is passed through it? What is its new length?

2. An aluminum wire is 3000 ft. long at 0° C. What is its length at 150° C.?

3. A wire is 100 cm. long at 20° C. At 80° C., it is 100.1104 cm. long. What is its coefficient of linear expansion?

4. At − 20° C. the steel cables of the George Washington Bridge are 8700 ft. long. How much will they increase in length if heated to 40° C.?

5. A brass rod is 60 ft. long at 0° C. To what temperature must it be heated to increase its length to 60.324 ft.?

6. A man buys 200 gallons of alcohol when the temperature is 0° C. He lets the unstoppered cans stand in a room which is 30° C. If they were full in the beginning, how much alcohol will overflow?

7. A gas measures 500 cc. at a temperature of 13° C. Find its volume when the temperature is 25° C.

8. A 1000-gallon tank is filled with gasoline at a temperature of 0° C. How much will overflow when the temperature rises to 25° C.?

9. A gas measures 3 quarts at 0° C. To what temperature must it be cooled to reduce its volume to 2 quarts?

10. Given 900 cc. of gas measured at S.T.P. (0° C. and 76 cm. pressure). Find its volume at 27° C. and 78 cm. pressure.

11. A clinical thermometer is graduated to give Centigrade readings. What Centigrade readings correspond to 92° F.? To 98.6° F.? To 110° F.?

12. Room temperature is considered as 68° F. What is it Centigrade?

13. The temperature of the electric arc is about 3600° C. What is its Fahrenheit temperature?

14. If alcohol freezes at − 130° C., calculate its freezing point on the Fahrenheit scale.

15. Change − 182° C., the boiling point of liquid air, to Fahrenheit.

16. If tungsten melts at 5432° F., what is its melting point on the Centigrade scale?

17. Reduce the following Fahrenheit temperatures to Centigrade: 190° F.; − 299° F.; 6332° F.; − 20° F.; 70° F.; − 450° F.; and − 252° F.

18. Reduce the following Centigrade readings to Fahrenheit: 1500° C.; − 273° C.; − 200° C.; − 40° C.; 4000° C.; 1780° C.; 1050° C.; 357° C.

X

Measurement of Heat

A. HEAT UNITS COMMONLY EMPLOYED

1. THE CALORIE

The metric unit of heat. We have already defined *the calorie* (see page 247) as *the quantity of heat needed to warm one gram of water through one degree Centigrade.* Conversely, it is the amount of heat lost when one gram of water cools through one degree Centigrade.

Biologists usually measure heat with the *large Caloric*, spelling it with a capital *C*. It is equal to 1000 small calories; that is, it is the amount of heat necessary to raise the temperature of 1000 grams (or one kilogram) of water one degree Centigrade.

2. THE BRITISH THERMAL UNIT (B.T.U.)

The English unit of heat. You learned about the B.T.U. on page 248. It represents the amount of heat required to raise the temperature of one pound of water through one degree Fahrenheit. *One B.T.U. equals 252 calories.*

How much work must be done to produce one B.T.U.? The apparatus devised to find out how much work must be done to produce one B.T.U. is so constructed that it wastes 100% of the energy put into it. (See Fig. 10–1.) In this apparatus, weights are permitted to fall a certain distance. In falling, the weights merely turn a set of paddles immersed in a known weight of water. The constant paddling of the water warms it by friction.

By multiplying the weight used by the distance it falls, you can easily calculate the number of foot-pounds of work wasted during the experiment. By multiplying the weight of water by the number of degrees Fahrenheit its temperature was raised during the experiment, you can calculate the number of British thermal units of heat produced by the wasted work. The average of a large number of experiments shows that *778 ft.-lb. of work are equivalent to one British thermal unit of heat.* In the metric system, *427 gram-meters of work are equivalent to one calorie.*

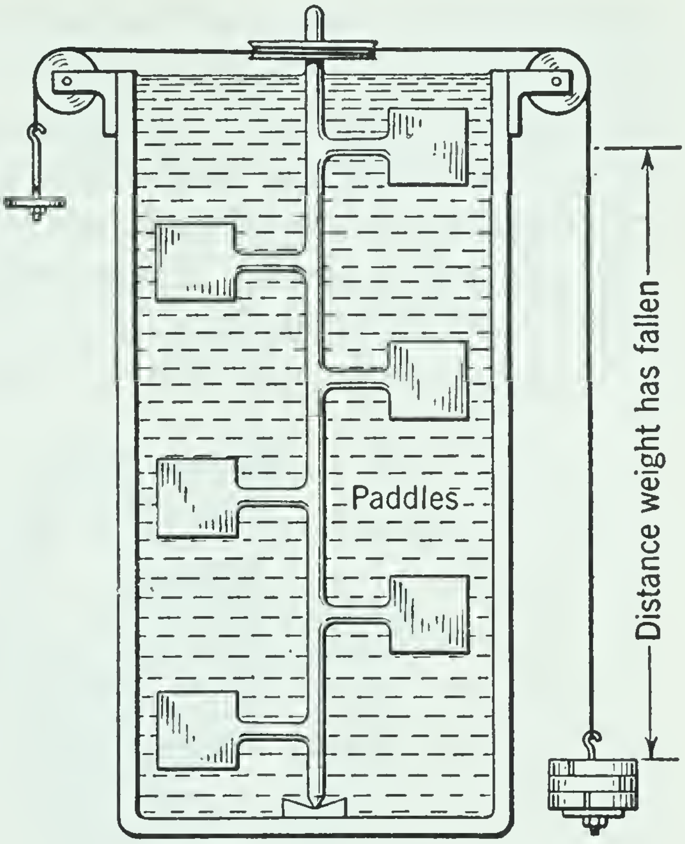


Fig. 10–1. An instrument designed to change all its energy into heat energy.

How is heat converted into work? It seems to be a poor rule that will not work both ways. If it is possible to waste work and produce heat, then it seems reasonable to believe that we can use heat energy to do work. This can be done in several ways. It can be shown by experiment that *one British thermal unit of heat can do 778 ft.-lb. of work,* and that *one calorie can do 427 gram-meters of work.* These numbers are called *the mechanical equivalents of heat.*

3. THERMAL EFFICIENCY

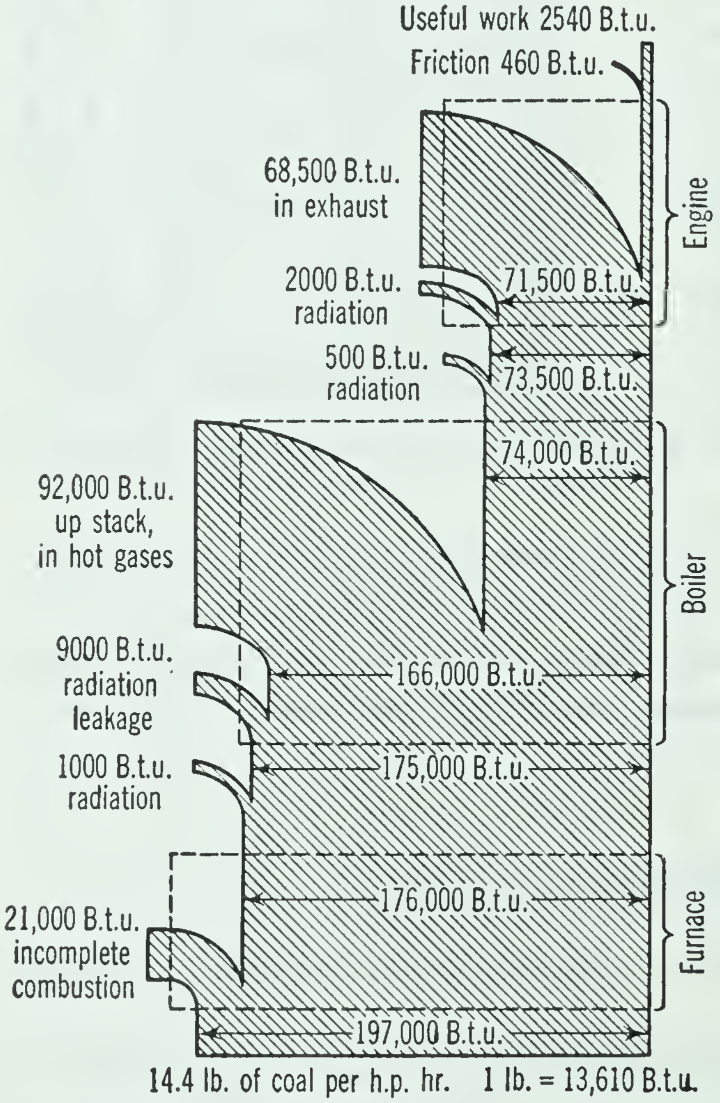
Let us mention briefly some of the methods used to make heat do work for us:

(1) *In our own bodies.* Biologists tell us that a thick slice of bread, when oxidized, furnishes *100 large Calories* or *100,000 small calories of heat.* Suppose that the bread is oxidized in your body and all converted into muscular energy. It is then capable of doing 42,700,000 gm.-m. of work. At an efficiency of 100%, that heat energy would enable you to climb a mountain almost 2500 ft. high, if your weight is 125 lb. Of course, part of the heat energy

which we derive from our food is used to keep the body temperature at 98.6° F., summer or winter. Some of our food is utilized for nutrition and repair. Experiments carried out by Professor Atwater of Wesleyan University showed that only 28% of the heat energy of a man's food was converted into muscular energy.

(2) *By use of steam.* When water is converted into steam, it expands about 1700 times and exerts pressure in all directions. In a steam boiler, the steam is confined until it reaches a high pressure. From the boiler it is led to the cylinder of a steam engine, where it expands and pushes a piston back and forth in the cylinder, thus doing work. B.T.U.'s of heat energy from the burning coal or oil produce the steam, and the steam in expanding produces the mechanical energy as it drives the piston to and fro.

Suppose that a pound of coal furnishes 14,500 B.T.U.'s. If all this heat is converted into work, one pound of coal is equivalent to 14,500 × 778 ft.-lb., or 11,281,000 ft.-lb. of work. For every pound of coal that is burned per hour, the engine should develop $\frac{11{,}281{,}000}{550 \times 60 \times 60}$ H.P. That is about 5.7 H.P. continuously. In practice, the ordinary steam engine uses about 1.5 lb. of coal to produce 1 H.P. per hour, an efficiency of about 11%.



Courtesy of J. A. Randall

FIG. 10–2. Diagram to show how heat energy is distributed in a furnace, boiler, and engine.

Some of the most efficient steam engines do not have an efficiency much above 20%.

Such low efficiency is not astonishing if we consider that nearly 30% of the heat energy goes up the chimney during combustion. About 50% of what remains is lost because it is impossible to use all the expansive force of the steam. The energy diagram, Figure 10–2, shows how the heat energy from a burning fuel is used or wasted in a power plant.

(3) *In internal-combustion engines.* In steam engines the fuel is burned beneath the boilers to produce steam. Such an engine we call an *external-combustion engine.* In gasoline engines, the fuel is burned inside the cylinders. They are examples of *internal-combustion engines.* A carburetor is used to vaporize the gasoline and mix it with air so that it will explode. The mixture of gasoline vapor and air is exploded in a thick-walled cylinder, usually by means of an electric spark. The heat energy from such explosions causes the gaseous products formed by the explosions to expand and push against the piston with great force.

The gasoline engine has an efficiency of 25–30%.

B. RELATIONS BASED ON HEAT UNITS

1. HEAT CAPACITY

Substances vary in heat capacity. Let us imagine the following experiment, which was devised by Tyndall, a famous English scientist: We have five metal balls, aluminum, iron, copper, zinc, and lead, and a five-pronged support. The balls are first placed in a flat-bottomed pan of boiling water to heat them all to the same temperature. Then they are placed upon a thin sheet of paraffin. The aluminum melts its way through the paraffin rapidly, followed by the iron. Although the aluminum ball is lighter, it absorbs more heat. The copper and zinc follow at almost the same rate, while the lead melts the paraffin slowly. If all the balls had the same weight, we would find that the aluminum absorbs the most heat in the boiling water, and it gives up most heat to the paraffin. We also conclude that of the five metals lead has the lowest capacity for absorbing heat. We conclude that some substances heat slowly and cool slowly because they have a high *heat capacity,* absorbing more calories while being warmed, and liberating more calories upon cooling. *The heat capacity of a body may be defined as the amount of heat needed to raise its temperature 1° C.*

2. LAW OF HEAT EXCHANGE

Calories lost equal calories gained. If your coffee is too hot, you may cool it by adding to it some cold water. Thus the coffee is cooled, but the water which you added is warmed, and the final temperature of the mixture will be some point between the two initial temperatures. If you touch a hot metal pan, your hand *gains* heat. If you touch a block of ice, your hand *loses* heat. Whenever we bring into contact two substances of *unequal* temperature, or mix them thoroughly, we find that *the warmer one loses heat* and that *the cooler one gains heat,* until both finally reach the *same* temperature. It is customary to say that heat flows from the warmer substance to the colder one. Prevost showed that in all such cases, *the total number of heat units lost by the warmer substance equals the total number of heat units gained by the cooler substance.* We shall find this statement, known as the LAW OF HEAT EXCHANGE, most useful in solving problems involving an exchange of heat.

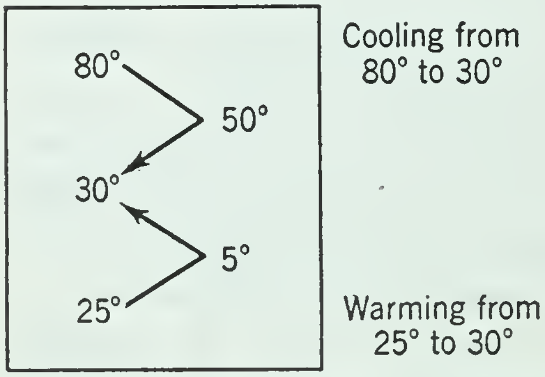


FIG. 10–3. Both substances reach the same final temperature.

In a laboratory experiment, 100 gm. of iron at 80° C. were added to 113 gm. of water at 25° C. The final temperature of the mixture was found to be 30° C. From Figure 10–3, in which the temperatures are all given, we see that the iron has cooled through 50° C., from 80° C. down to 30° C. We note that the water was warmed from 25° C. to 30° C., a change in temperature of 5° C. Then, 100 gm. (wt. of iron) × 50 (change in temp.) × 0.113 (sp. ht. of iron) = 565, the number of calories lost by the iron. And, 113 gm. (wt. of water) × 5 (temp. change of water) × 1 (sp. ht. of water) = 565 calories, gained by water. If any one of the six quantities is unknown it may be found from the equation:

Calories lost = calories gained.

Demonstration. Mix 100 cc. of ice water (0° C.) with 100 cc. of boiling water (100° C.) in a 300 cc. beaker. Stir the mixture with a Centigrade thermometer and note the resulting temperature. Compare the results of this experiment with the fundamental heat equation, calories lost = calories gained.

3. SPECIFIC HEAT

The ratio of a substance's heat capacity to that of water. Water heats slowly and cools slowly. It has the highest heat capacity of any ordinary substance. From the definition of the calorie, we conclude that the *heat capacity of water is one.* Since the word "specific" implies a ratio, then the *specific heat of a substance is the ratio of its heat capacity to that of water.*

We may define specific heat in terms of the heat units. For example, the *specific heat of a substance is equal to the number of calories needed to raise the temperature of 1 gm. of the substance 1° C.* In the English system, it is the number of *B.T.U.*'s required to raise the temperature of 1 lb. of the substance 1° F. *The specific heat of water is one.*

By experiment, it is possible to show that a given weight of iron when heated rises in temperature about 9 times as fast as the same weight of water. We find that its specific heat is only about $\frac{1}{9}$ as much as that of water. The average of a large number of trials shows that it takes only 0.113 calorie to warm one gram of iron 1° C. Hence, the specific heat (sp. ht.) of iron is 0.113. From the Appendix, Table 5, we see that the specific heat of most substances is rather small when compared to that of water.

What facts can we infer from simple arithmetic? If 1 calorie warms 1 gm. of water 1° C., then 100 calories will warm 100 gm. of water 1° C., or 100 calories will warm 1 gm. of water 100° C. In all cases of this kind, it follows that: *weight (in gm.) × change of temperature (C) × sp. ht. = calories*, or, *weight (in lb.) × change in temperature (F) × sp. ht. = B.T.U.'s.*

To illustrate: we find the number of calories needed to raise the temperature of 300 gm. of iron through 50° C. by multiplying its weight (300 gm.) by its change in temperature (50° C.) by its specific heat (0.113). Or, suppose that we wish to find the number of calories that 200 gm. of water will liberate in cooling from 80° C. to 20° C. Calories = weight (200 gm.) × temperature change (80° C. − 20° C.) × specific heat (1).

How can specific heat be measured? The method of mixtures is generally used for finding the specific heat of a substance. Suppose that we have a lump of brass of which we wish to find the specific heat. We weigh a calorimeter, or metal cup, of known specific heat. Then some cold water is added to the calorimeter and the combined weight of calorimeter and water is found. The lump of brass is then weighed and suspended in steam arising from boiling water. Probably the temperature is 100° C. Next the cold water is stirred with a thermometer and its temperature is taken. Then the brass is quickly transferred to the cold water. Of course there is some loss of heat while such transfer is being made. (See Fig. 10–4.) The water is stirred with the thermometer until the mercury stops rising. The temperature at which this occurs is the final temperature of the mixture. The brass has been cooled, and the water and the calorimeter have been warmed. Let us assume the following data:

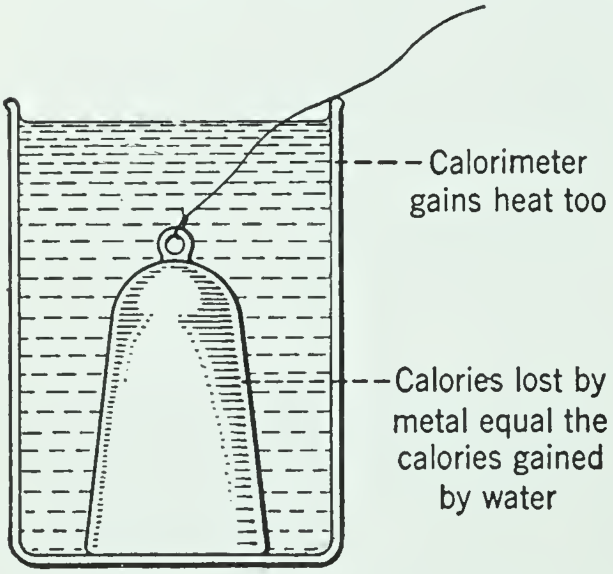

Calorimeter gains heat too
Calories lost by metal equal the calories gained by water

Fig. 10–4. Metal loses heat and water gains heat.

Weight of calorimeter	110 gm.
Specific heat of calorimeter	0.09
Weight of water	405 gm.
Weight of brass	201.9 gm.
Initial temperature of the water	20° C.
Initial temperature of calorimeter (same as initial temperature of water)	20° C.
Initial temperature of brass	100° C.
Final temperature of water (and calorimeter) and brass	23.5° C.

The brass loses heat as follows:

Weight (gm.) × change of temperature × specific heat = calories. Or, $201.9 \times (100\text{–}23.5) \times x =$ calories.

The calorimeter and the water gain heat as follows:

$110 \times (23.5 - 20) \times 0.09 = 34.65$ calories, gained by calorimeter.
$405 \times (23.5 - 20) \times 1.00 = 1417.5$ calories, gained by water.
Total calories gained $= 1452.15$.

By Prevost's theory, *heat lost equals heat gained.*

Then, $201.9(76.5)x = 1452.15$ calories.
Whence, $x = 0.094$, the specific heat of brass.

This method is a general one. In all problems involving heat exchange and specific heat, the student needs to consider *which substances lose heat and which gain heat;* he should bear in mind the fact *that calories gained equal calories lost;* and he must remember *that weight in grams times change in temperature in degrees Centigrade times specific heat equals calories.*

Demonstration. Determine the specific heat of a block of metal, such as aluminum, as follows:

Method. Tie a piece of strong, light twine to the solid and then weigh it. (Students get more satisfactory results when a block of metal is used instead of metal shot. A block of aluminum shaped like that of Figure 10–4 is more satisfactory than lead or copper, since it has a much higher specific heat.) Put the solid in a boiler half full of water, letting the string hang over the edge so the solid may be easily removed. Light your burner. While the water in the boiler is heating, weigh a calorimeter, fill it about $\frac{2}{3}$ full of water, and weigh again. The water used should be about 4° colder than room temperature. Take the temperature of the steam arising from the boiling water. (This is also the temperature of the solid.) Stir the water in the calorimeter with a thermometer, and take its exact temperature *just before* the solid is to be introduced. By means of the cord, lift the solid just above the surface of the water and hold it in the steam for a full half minute. Thus the solid is dried thoroughly. Then transfer, as quickly as possible, the solid to the calorimeter of cold water. Stir with the thermometer, and also agitate the water by lifting the solid up and down slowly. When the mercury stops rising, read the thermometer. In your calculations, remember that both the calorimeter and the cold water have gained heat. The metal block lost as many calories as the calorimeter and water gained. Since there was no change of state, *weight in gm.* × *change in temperature* × *specific heat* = *calories.*

DATA

Weight of calorimeter gm.
Specific heat of calorimeter. (See Appendix A, Table 5)
Weight of calorimeter and water gm.
Weight of water gm.
Weight of metal block gm.
Original temperature of water and calorimeter ° C.
Original temperature of metal ° C.
Final temperature of water, calorimeter, and metal ° C.
Calories gained by calorimeter (wt. × temp. change × sp. ht.)
Calories gained by water (wt. × temp. change × 1)
Total calories gained
Total calories lost (same as calories gained; wt. of metal × change in temp. × sp. ht.)
Calories lost by metal in cooling 1° Centigrade
Calories lost by 1 gm. of metal in cooling 1° C. (sp. ht.)

Compare the specific heat determined with the accepted value. (See Appendix A, Table 5.) What is the per cent of error?

4. APPLICATIONS—WATER AS A COOLANT

How does high specific heat of water affect us? On one of those rare days in early June, the air in the latitude of New York may seem quite warm. If you are rash enough to take a dip in some lake, you find the water decidedly cold. The water warms much more slowly than the land. In October, the reverse is true. The air may be chilly, but the water will feel quite warm. Water cools slowly. It takes quite a long time to heat a quart of water to its boiling point. In a hot-water bottle in the sickroom two quarts of water will remain warm almost all night. Because of its high specific heat, water is widely used as a medium for carrying heat away from certain machines which need to be kept cool, for example, gasoline engines and ice-plant condensers.

Along the Great Lakes regions there is a fruit-growing belt. The area warms up more slowly in the spring and the fruit trees do not bloom early enough to be nipped by late frosts. In the fall the water retains the heat and early frosts are not likely to destroy the fruit before it matures.

Cities located on large bodies of water are not subject to so great extremes of temperature as inland cities. There is not much difference in latitude between San Francisco and St. Louis. But San Francisco, tempered by the Pacific Ocean, has a more equable climate than St. Louis. New York City is on the ocean, but its climate is subject to greater extremes than that of San Francisco because it is affected by the westerly winds which blow across the continent.

One of the coldest spots on the earth is Northern Siberia. It is far distant from any large body of water except the Arctic Ocean, and that ocean cannot moderate its climate to any marked degree.

SUMMARY

1. Heat is the result of molecular motion. Intensity of heat is measured in degrees, Fahrenheit or Centigrade; quantity of heat is measured in calories or British thermal units (B.T.U.).
2. The mechanical equivalent of heat is stated as follows: 778 ft.-lb. of work are equivalent to one B.T.U. In this metric system, 427 gram-meters of work are equivalent to one calorie.
3. Heat is converted into work by our bodies, by steam engines through the use of steam, and by internal combustion engines.
4. The law of heat exchange: *heat lost = heat gained.*
5. The specific heat of a substance is the number of calories required to raise the temperature of 1 gm. of that substance 1° C.

Weight in gm. × change in temperature (Centigrade) × specific heat equals calories. Weight in lb. × change in temperature (Fahrenheit) × specific heat equals B.T.U.'s.

How many of the following terms can you define or explain?

Mechanical equivalents of heat
Thermal efficiency
Specific heat
Law of heat exchange

SELF-TESTING EXERCISES

Complete These Statements

On a separate sheet of paper numbered from 1 to 4 write the words needed to fill correctly the blank spaces in the following sentences.

Water heats slowly and cools slowly because it has a high ..(1)... One B.T.U. is equivalent to ..(2).. foot-pounds of work. The substance used as a standard for specific heat is ..(3)... The ordinary steam engine has an efficiency of about ..(4)..%.

Are These True or False?

On a separate sheet of paper numbered from 1 to 5 write a T *or an* F *to show whether each statement is true or false.*

1. The specific heat of iron is 0.113. That means that it takes about nine times as much heat to warm one gram of water one degree as it does to warm one gram of iron one degree.
2. When water is converted into steam it expands about 1700 times.
3. Alcohol has a specific heat of 0.65; therefore it is a better coolant than water whose specific heat is one.
4. The heat capacity of a body is the amount of heat needed to raise the temperature of the body 10 degrees.
5. One B.T.U. equals 252 calories.

QUESTIONS

1. Why is the climate along the shores of lakes Erie and Ontario suitable for fruit-growing?
2. Which will keep warm longer in a sickroom, a 7-lb. flatiron, or 4 lb. of hot water, if both have the same original temperature?
3. What is the meaning of the expression, "A thick slice of bread furnishes 100 large Calories"?

4. Compare the climates of New York and Honolulu. How do you account for the difference?

5. Compare the specific heats of iron and copper. Why is copper used in making soldering irons but not in making flatirons?

6. Compare alcohol with water in terms of cooling capacity in the radiator of a car.

7. If an iron bullet and a lead bullet of equal weight were fired at equal speeds against a target, which would be heated more?

8. Why does land become colder at night than an adjoining lake?

PROBLEMS

1. How many calories are needed to warm 500 gm. of iron 40° C.? How many calories are needed to warm 500 gm. of lead 40° C.?

2. A calorimeter weighs 110 gm. Its sp. ht. is 0.1. If it has a temperature of 10° C., how many gm. of water at 50° C. must be poured into it to raise its temperature to 35° C.?

3. How many B.T.U.'s will be needed to raise the temperature of 50 lb. of stone from 40° F. to 500° F., if the sp. ht. of stone is 0.4?

4. Three hundred grams of metal at 98° C. are mixed with 526 gm. of water at 20° C. If the temperature rises to 26° C., what is the sp. ht. of the iron?

5. A calorimeter, sp. ht. equals 0.1, contains 100 gm. of water at 20° C. A platinum ball weighing 60 gm. is taken from a furnace and plunged into the water. The temperature of the water and calorimeter rises to 45° C. What was the temperature of the ball?

6. Two hundred grams of metal having a temperature of 100° C. are plunged into 400 gm. of water at 20° C. The temperature rises to 28° C. What is the sp. ht. of the metal?

7. When 500 grams of water at 80° C. is poured into 400 grams of water at 20° C. what is the temperature of the mixture?

8. A sled is drawn over the ice with a pull of 80 lb. The equivalent of how many B.T.U.'s will be produced if the sled is drawn 2 miles?

9. How many B.T.U.'s of heat energy does a 200-lb. man use in climbing a mountain 4000 ft. high?

10. If your body works at an efficiency of 28%, how many meters can you climb on the energy from a thick slice of bread (100,000 calories), if your weight is 60 kgm.?

11. Under a boiler 2000 lb. of coal are burned every hour. If each pound of coal yields 12,000 B.T.U.'s, what horsepower engine, working at an efficiency of only 15%, can be operated by this boiler? How much energy is wasted?

XI

Machines Utilize Effects Produced by Changes in State

A. MELTING AND FREEZING

1. CRYSTALLINE AND NONCRYSTALLINE SUBSTANCE

What is fusion? When a solid is warmed, it absorbs heat. At a certain temperature, it changes from the solid to the liquid state. *The process of changing from the solid to the liquid state is called fusion.* It is also known as *melting*, or *liquefaction.* The temperature at which such a change occurs is called the *melting point. Pure* substances generally have a *definite* melting point, and different solids have different melting points. The determination of the melting point of a solid is often used as a test for its purity.

When a substance changes from a liquid to a solid state, the process is called *solidification.* You have already learned that some of the solids formed in this way crystallize in regular geometric forms. The temperature at which solidification begins is known as the *freezing point.* For crystalline substances the melting point and the freezing point have the same temperature.

Noncrystalline substances like glass and sealing wax have no definite melting point, but they soften gradually when heated. Such substances may be heated until they soften and then be bent, molded, or welded. Wrought iron becomes plastic when it is heated. The blacksmith heats two pieces of wrought iron until they begin to soften, and then pounds them together into a single piece by a process known as *welding.* Cast iron has a sharp melting point, and it cannot be welded in this manner. If two or more metals are melted together, an *alloy* may be formed. In some cases, the alloy seems to be a mixture of the metals; in a few cases, the proportion is definite, and a compound appears to have been formed; in the majority of cases, the alloy is a *solid solution* of one or more metals in another metal. When such alloys cool, crystals of one metal may separate.

An alloy may have properties unlike those of any of its constituents, or its properties may be intermediate, somewhat like each constituent. Usually the melting point of the alloy is lower than the average melting point of its constituents, and in many cases it is lower than the melting point of any one of them. For example, "Wood's metal" (consisting of tin, lead, bismuth, and cadmium) melts at 65.5° C., although the lowest melting point of any of its constituents (that of tin) is 231.9° C. Use is made of such alloys in automatic fire-alarm systems and automatic fire sprinklers, and in sealing tin cans.

The tensile strength of a substance is reduced as its temperature rises. Structural material, such as steel, may collapse during a fire as a result of such weakening, even before the melting point is reached. In some cases, this seems to be the reason for the collapse during a fire of so-called fireproof buildings.

How does the volume change upon solidification? When molten paraffin is poured into a tumbler and permitted to solidify, the center will be found depressed. (See Fig. 11–1.) Paraffin contracts when it solidifies. Many metals and alloys behave in the same manner. In fact, *noncrystalline* substances tend to *contract* upon solidification.

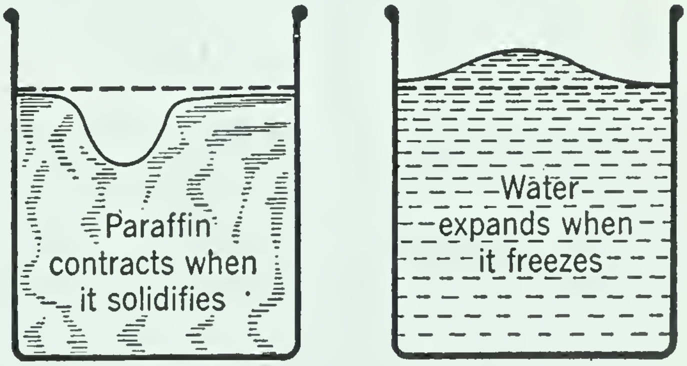

Paraffin contracts when it solidifies
Water expands when it freezes

FIG. 11–1. Some liquids expand upon freezing, others contract.

In winter, you may find water pitchers broken by the force of expansion of the water as it freezes. On cold mornings, you can see milk bottles, with the frozen milk extending up above the neck of the bottle. Water pipes may burst if the water in them freezes, and automobile radiators that have cracked from the expansive force which water exerts upon solidifying are too common. The volume occupied by ice is about 1.1 times that occupied by the water from which the ice was formed. The force of expansion is enormous. You can find rocks split by the expansive force exerted when water flows into crevices and then freezes. There is a mistaken idea common in some localities that water pipes do not burst when they freeze, but that they burst when the pipes are thawed out. Of course the pipes do not show a leak until the ice inside has melted.

Bismuth and antimony expand upon solidification. Antimony is a constituent of type metal. Because it expands when the molten metal is poured into a mold, the type will be sharp and clear-cut. We find that *crystalline* solids tend to *expand* when they change from the liquid to the solid state.

DEMONSTRATION. Fill a metal ice bomb with cold water, screw in the plug, and place it in a freezing mixture of dry ice and ether, or in a mixture of crushed ice and salt. Allow the bomb to remain in the freezing mixture until it breaks. As soon as it breaks, examine the inside for the presence of ice. In freezing, what volume change took place in the water?

Fill a small beaker level full of melted paraffin, then cool it by holding the beaker in cold water. After it has solidified is there any evidence of a volume change in the paraffin?

How does the expansion of water upon freezing help us? Naturally, you are not pleased to have water expand and burst your water pipes and milk bottles. But let us inquire what would happen if water contracted upon solidifying. Ice would be denser than water. The first layer of ice formed at the surface of a lake would sink. Other layers would sink as soon as formed until the entire body of water would be frozen solid in winter. The Great Lakes, as well as other lakes and streams in the middle latitudes, would be frozen solid throughout.

The sun's heat rays do not penetrate water to any considerable depth. The lakes would not thaw out even in summer, except to a slight depth. Fish and all forms of aquatic life would perish in the Temperate Zones, and our lakes and streams would be closed to navigation.

How does pressure affect the melting point? When snow is soft, it will "pack." When you make a snowball, the snow at the surface melts under the pressure which you apply. It freezes again as soon as you release the pressure, and the shell of ice thus formed holds the snowball together. Such behavior is characteristic of solids that *expand* upon freezing. Their *melting point is lowered by pressure.*

Let us suspend two weights by means of a strong wire over the surface of a cake of ice. (See Fig. 11–2.) The pressure directly beneath the wire lowers the melting point of the ice, and the weights pull the wire into the ice. As the pressure is then released, the water above the wire freezes again. Thus the wire will cut its way through the ice, but the block will still be solid ice after the wire has passed entirely through the cake. Such *freezing again after the pressure is released on water melted under pressure is called regelation.* Much of the movement of valley glaciers is due to regelation.

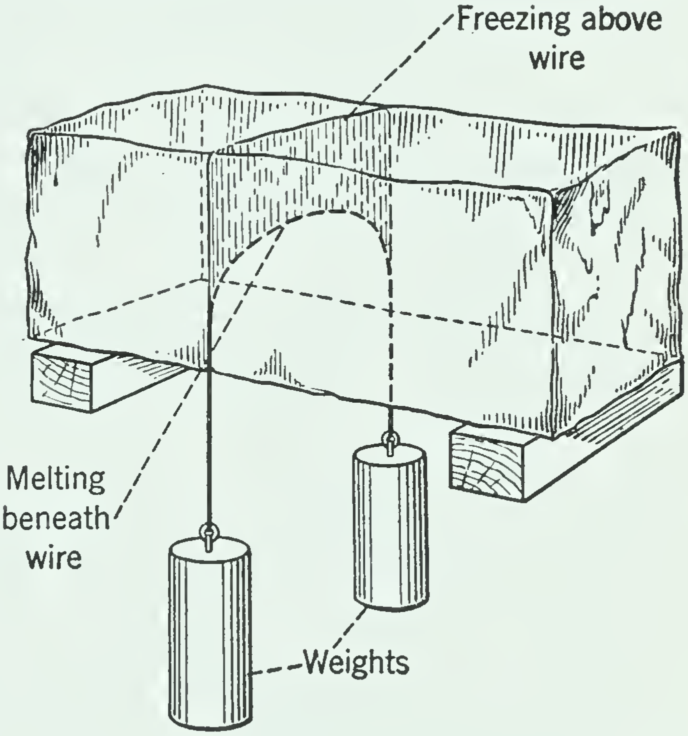


Fig. 11–2. Pressure lowers the melting point. The freezing again of the water is regelation.

A great pressure is needed to lower the melting point of ice very much. For example, a pressure of one atmosphere reduces the melting point only 0.0075° C. If snow is very much colder than 0° C., it will not "pack" readily.

If we increase the pressure on a substance such as paraffin, which contracts when it solidifies, its melting point is increased. You will note that the behavior of such substances is just the opposite of that of substances which expand when they freeze. Some rocks in the interior of the earth are probably hot enough to melt at normal pressure, but they remain solid because they are under stupendous pressure. If the pressure is released, they melt and form the lava of volcanoes.

2. HEAT OF FUSION

How much heat is needed to melt one gram of ice? Suppose we put a pan of ice water containing a few lumps of ice on a gas burner and stir the mixture all the time the ice is being melted. The temperature is 0° C. when we begin and it does not rise above 0° C. until all the ice is melted. Heat is certainly being absorbed; but since the temperature does not increase, it is evident that the heat is being used merely *to melt the ice.* *The number of calories needed to melt one gram of a substance without increasing its temperature is called its heat of fusion.* At one time it was known as *latent* (hidden) heat, because a thermometer does not show any evidence of its presence. The average of a large number of carefully performed experiments shows that it requires approximately 80 calories of heat to convert 1 gm. of ice at 0° C. into 1 gm. of water at 0° C. In melting, ice takes heat from the substances around it, thus lowering their temperature. Because ice has so high a heat of fusion, it makes an excellent refrigerating agent. It requires 144 B.T.U. to change 1 lb. of ice at 32° F. into water at 32° F.

In the heat of fusion, we have an example of the effect of heat in producing a change of state. Figure 11–3 shows what happens when we *add* heat to a solid. If we *subtract* enough heat from a liquid, it will solidify. To convert 1 gm. of ice water at 0° C. into ice at 0° C., we must *subtract* 80 calories of heat.

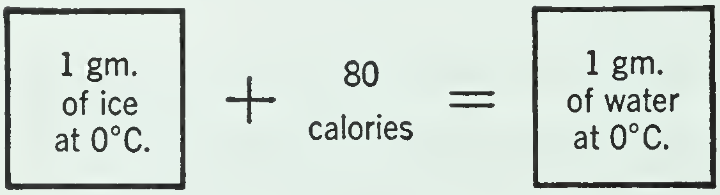


Fig. 11–3. Heat of fusion.

How can heat of fusion be measured? To find the number of calories needed to melt one gram of a solid, which is its heat of fusion, we use the method of mixtures. We know that hot water will melt ice, for example, and we can find how many grams of ice can be melted by a known weight of water at a known temperature. We need the following data: weight of calorimeter; specific heat of calorimeter; weight of water; weight of ice; initial temperature of hot water; and the final temperature when all the ice is melted.

PROBLEM. A calorimeter weighing 100 gm. has a sp. ht. of 0.09; it contains 400 gm. of water at 40° C.; 91 gm. of *dried* ice are introduced. When the ice is all melted the temperature is 18.2° C. What is the heat of fusion of the ice?

Solution. Both calorimeter and water lose heat as follows:

$100 \times (40 - 18.2) \times 0.09 = 196.2$ calories (lost by calorimeter).
$400 \times (40 - 18.2) \times 1.00 = 8720$ calories (lost by water).
Total calories lost = 8916.2.

These 8916.2 calories did two things: first, they melted 91 gm. of ice; second, they warmed the 91 gm. of water thus formed from 0° C. to 18.2° C.

$91 \times (18.2 - 0) \times 1.00 = 1656.2$ calories gained by water.

$8916.2 - 1656.2 = 7260$ calories, which were used to melt the ice.

$7260 \div 91 = 79.8$ calories used to melt 1 gram of ice, or its heat of fusion.

SUGGESTION. The student will do well to remember that one gram of ice water is formed for every gram of ice that melts. As this ice water is being warmed to the final temperature, it takes part of the heat from the hot water.

DEMONSTRATION. Find how many calories are required to melt one gram of ice using the method of mixtures.

Weigh the calorimeter; fill it half full of water at about 35° C., and weigh again. Break up two hundred grams of ice into lumps about one inch across. Estimating to tenths of a degree, read the temperature of the water in the calorimeter. Add ice to the calorimeter, a few lumps at a time. Be careful to wipe each piece of ice free from adhering moisture before introducing it into the calorimeter, since the chief source of error in this experiment arises from the introduction of water with the ice. Stir the water constantly, adding more ice from time to time until the temperature is reduced to about 5° C. When the ice is *all* melted, take the temperature. Weigh the calorimeter and contents. The increase in weight equals the weight of ice added.

Record the following data on a sheet of paper or in your notebook.

DATA

Weight of calorimeter
Specific heat of calorimeter
Weight of calorimeter and water
Weight of water
Initial temperature of water and calorimeter
Final temperature of water and calorimeter
Weight of calorimeter and water, after adding ice
Weight of ice used
Number of calories lost by calorimeter
Number of calories lost by water (cooling to final temperature)
Total calories lost
Total calories gained (by ice and ice water)
Calories gained by ice water (wt. of ice × [final temperature − zero] × 1)
Calories used to melt x gm. of ice
Calories used to melt 1 gm. of ice (heat of fusion)

Compare the result with the accepted value.

Heat is set free when water freezes. We have learned that heat must be added to a solid to melt it. When a liquid solidifies or freezes, it seems natural to expect that heat will be liberated, because energy is indestructible. As a matter of fact, when one gram of water at 0° C. freezes, it sets free 80 calories of heat to the surrounding medium. The air in winter is warmed by the heat liberated during the formation of snow and ice. For this reason, the weather often moderates just before or during a snowstorm. Tubs of water in cellars may give off enough heat upon freezing to protect canned fruits and vegetables from freezing.

3. EFFECT OF IMPURITIES ON THE FREEZING POINT

Heat is absorbed in solution. Dissolving salt in water lowers the temperature. A still more decided lowering of the temperature occurs when sal ammoniac, potassium iodide, or ammonium sulfocyanide is dissolved. Some of the heat energy of the solvent is used in dissolving the solute. Because heat energy breaks down the solid, heating the solvent not only causes a substance to dissolve more rapidly, but in almost all cases it increases the total quantity that can be dissolved.

When are freezing mixtures necessary? We cannot make ice cream or frozen puddings by the use of ice alone. The melting point of the ice is approximately the same as that of the substance to be frozen. When salt is put on ice it dissolves in the surface moisture. But a solution of salt in water freezes at a lower temperature than pure water. In fact the freezing point of a saturated solution of salt in water is − 22° C. Since the salt solution has a lower melting point than water, salt added to ice makes the ice melt rapidly. Both the melting of the ice and the dissolving of the salt absorb heat. Taking heat from the cream or the pudding lowers its temperature. If we continue to take heat away from a liquid, it will eventually be cooled below its freezing point.

Demonstration. Place a test tube containing a water solution of salt into a beaker with dried ice and ether. Insert a thermometer into the test tube and note the temperature at which the salt solution begins to freeze. Dissolved substances have what effect upon the freezing point of water?

B. EVAPORATION AND CONDENSATION

What is vaporization? Just as the addition of heat to a solid changes it into a liquid, so a liquid may be changed into a gas or vapor by the addition of heat. The process of converting a liquid into a vapor is called *vaporization.* As the liquid is warmed, the more rapidly moving molecules escape from the surface. We call this process *evaporation.*

If we put a basin of water over a gas flame, bubbles of water vapor soon begin to form at the bottom of the basin. As these bubbles rise through the cooler layers of liquid above them, they collapse, causing the familiar "singing" so often noticed before liquids begin to boil. When the entire liquid is hot enough so that these bubbles reach the surface freely, vaporization occurs throughout the liquid with visible disturbance. Such vaporization is called *boiling.*

How fast do liquids evaporate? So many factors affect the rate at which liquids evaporate that there is no short answer to this question. Since molecules disappear from the surface of the liquid during evaporation, anything that causes molecules to escape from the surface more rapidly will accelerate evaporation.

1. EVAPORATION DEPENDS ON SIX FACTORS

(1) *Effect of temperature.* You know that hot water evaporates faster than cold water. This is what you would expect because heat increases the rate at which the molecules move. Therefore, we conclude that *the rate of evaporation increases with an increase in temperature.*

(2) *Effect of area.* Suppose that we have a quart of water in a deep, narrow vessel and another quart in a broad, shallow pan. Common sense leads us to believe that more molecules can escape in a given time from a surface of 100 sq. in., for example, than from one of 5 sq. in., and the facts justify our belief. *The rate of evaporation increases as the surface area of the liquid increases.*

(3) *Effect of air above liquid surface.* If you wished to break the world's record in a 100-yd. dash, you would not go to a busy street intersection in a city. Too many collisions would block your progress. There is no doubt that some of the water molecules, in attempting to escape from the surface by evaporation, collide with air molecules. Some of them doubtless rebound into the liquid again. (See Fig. 11–4.) If some of the air above the liquid surface is removed, the collisions will be less frequent, and the rate of evaporation will be accelerated. It becomes very rapid in a vacuum. Hence we conclude that the *rate of evaporation is increased when the atmospheric pressure is reduced.*

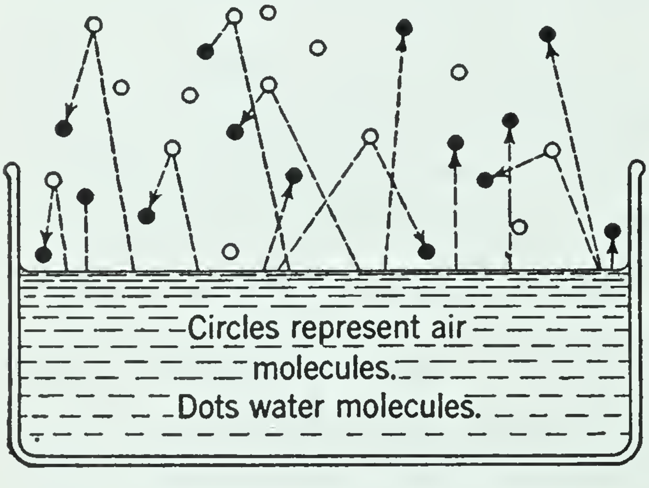


Fig. 11–4. Air molecules retard evaporation.

Demonstration. Place equal quantities of ether in two evaporating dishes. Place one under the bell glass of a vacuum pump and start the pump. Leave the other dish in air. Compare the rates of evaporation in the two cases. Reduced pressure has what effect upon the rate of evaporation of a liquid?

(4) *Effect of humidity.* As water molecules escape from the surface, they occupy a part of the space between the air molecules, thus making a more crowded barrier for the molecules trying to escape. (See Fig. 11–5.) Now some water molecules will collide with *other water molecules* and rebound to the liquid. As the air becomes more nearly saturated with water vapor, the evaporation will be very slow. When the number of water molecules returning per second to the water surface exactly equals the number of water molecules escaping per second, the air is *saturated with water vapor. The rate of evaporation of water is decreased when the humidity of the air is increased.*

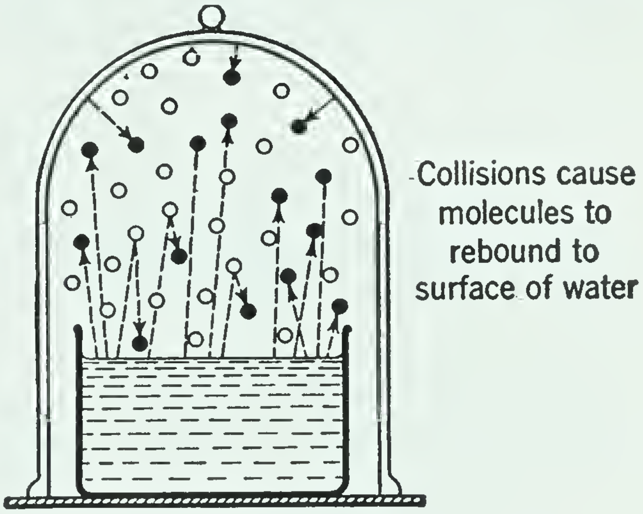


Fig. 11–5. Vapor is saturated.

(5) *Effect of wind or circulation.* Wet clothes dry rapidly on a windy day. The perspiration evaporates rapidly from your body when you sit in a draft. The saturated air in the immediate vicinity is removed by the wind and replaced by fresh, unsaturated air. We conclude that *the rate of evaporation increases with the rate of change of the air in contact with the liquid surface.*

(6) *Nature of liquid.* Alcohol evaporates much faster than water; ether evaporates much faster than alcohol; but some liquids like glycerine and olive oil hardly evaporate at all. We find that the *rate of evaporation varies with the nature of the liquid itself.*

Do solids evaporate? Suppose washed clothing is hung out of doors on a cold day. The water freezes, but in a few hours you will find that the clothes will be dry, even though the temperature was below freezing all the time. The ice must have evaporated. The molecules of solids are in constant motion, too, but they move more slowly than those of liquids. Such solids as snow and ice, camphor gum, iodine, musk, and "moth balls" (naphthalene) slowly disappear by evaporation. The vapor pressure of ice at 0° C. is equal to about 4.5 mm. of mercury. If a substance passes from a solid to a gaseous state, without appearing to liquefy, and then condenses again directly to a solid, it is said to *sublime.* Such solids as iodine can be purified by *sublimation.*

2. BOILING

How does pressure affect the boiling point? Let us refer to Table 8 of Appendix A, to see how raising the temperature affects the pressure which the water vapor exerts contrary to the air pressure above its surface as it escapes by evaporation. We may think of these two forces as opposing one another, the water molecules trying to escape, and the air pressure on the surface of the liquid trying to prevent their escape. Let us plot a curve, using the horizontal axis of the graph for the pressures at twenty-degree intervals from 0° C. to 100° C. and using the vertical axis of the graph for the pressures. (See Fig. 11–6.)

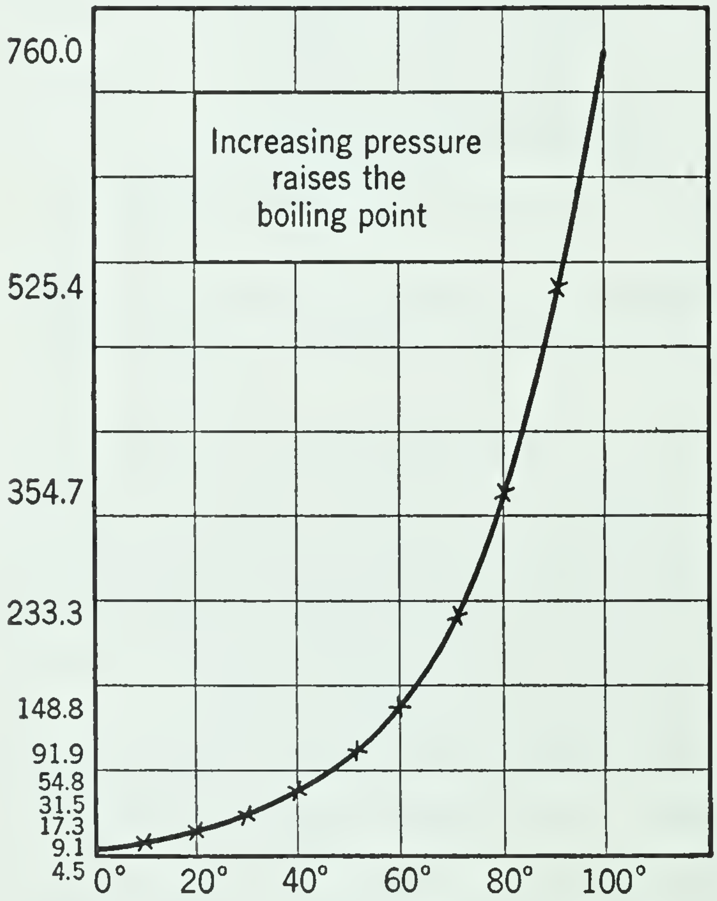


Fig. 11–6. Boiling point varies with pressure.

At a temperature of 100° C., the pressure of water vapor is 760 mm. of mercury, or one atmosphere. We say that the *boiling point of water at 760 mm. of mercury is 100° C.*, because at that temperature its saturated vapor exerts a pressure equal to that amount. If the air pressure is reduced to 525.4 mm. of mercury, water will boil at 90° C. If we increase the pressure to 787 mm. of mercury, water boils at 101° C. If we reduce the pressure to 733 mm., water boils at 99° C. Thus, we find that *the boiling point of water increases as the air pressure upon its surface increases.* Near the boiling point, a variation in pressure equal to 27 mm. of mercury will cause a variation of 1° C. in the boiling point.

Why is pressure cooking necessary? If you live in Denver, Colorado, or in Quito, Ecuador, you find that the air pressure is so low that water boils at from 90° C. to 95° C. At an elevation of about 900 ft. above sea level, the boiling point of water is about 1° C. lower than at sea level. At Denver, then, about one mile above sea level, boiling water is hardly hot enough to hard-boil eggs, and it takes a long time to cook potatoes and vegetables by boiling.

At high altitudes, pressure cookers are much used. Such cookers are strong-walled vessels. The foods are put into the cooker, a little water added, and then a thick lid is clamped on so tightly that steam cannot escape. When the water boils, the pressure of its saturated vapor is *added* to the pressure of the air inside the cooker. As the pressure rises, the boiling point rises, too. In such a cooker the temperature may rise to 110° C., or even to 120° C. Foods cook at 110° C. in about half the time required at 100° C. At a gauge pressure of 25 lb., potatoes cook in about 10 minutes and a pot roast is finished in about 40 minutes. To save time, pressure cookers are also used in many lo-

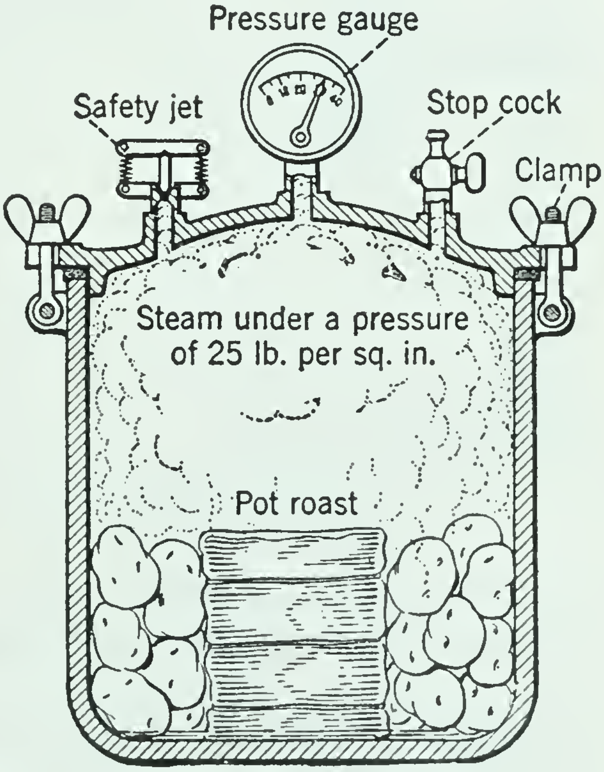


Fig. 11–7. Cooking under increased pressure.

calities at low altitudes. They find use in canning vegetables and meats, since sterilization is more complete at higher temperatures. (See Fig. 11–7.)

How are vacuum pans used? Let us take a round-bottomed flask, add to it a little water, and heat the water to boiling. Then we may remove the flame and stopper the flask tightly. Let us next turn the flask upside down and clamp it in position as shown in Figure 11–8. The flask is full of water and steam. If we dip a sponge in cold water, and let the water flow over the bottom of the flask, some of the steam inside condenses and produces a *partial vacuum.* The water will start boiling vigorously under the reduced pressure. When the boiling stops, it can be started again by applying more cold water. The experiment can be continued until the water is boiling at about room temperature.

The principle of boiling under reduced pressure is used in *vacuum pans.* Sugar crystals may be obtained by boiling sugar syrup in a vacuum pan. The liquid evaporates more rapidly, and the temperature is low enough so that there is no danger of scorching the sugar. Dyestuffs and other chemicals are dried in this manner.

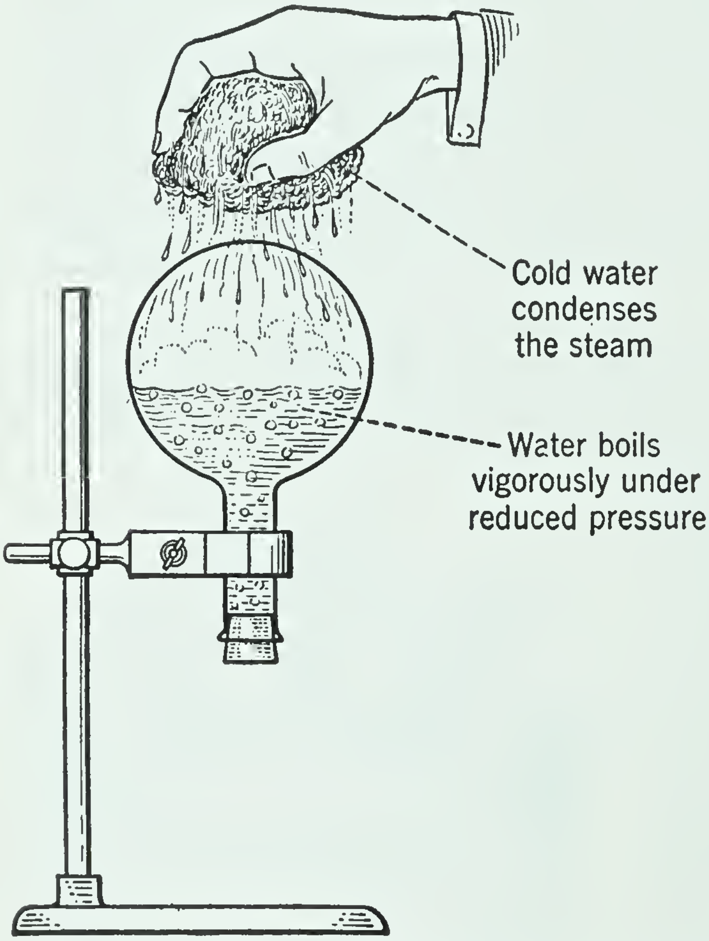

Cold water condenses the steam
Water boils vigorously under reduced pressure

FIG. 11–8. Lowering the pressure lowers the boiling point.

DEMONSTRATIONS. 1. Try the experiment described above and illustrated in Figure 11–8.

2. Exhibit a steam pressure cooker and study its various parts. (See Fig. 11–7.)

What are the laws of boiling? Several facts concerning boiling liquids have been determined. We know that a liquid does not boil until the pressure of its saturated vapor equals the pressure upon the surface of the liquid. The temperature at which this condition occurs is called the *boiling point.*

(1) The boiling point is sometimes used to identify liquids or to determine their purity. This is possible because *every pure liquid has a definite boiling point under the same conditions of pressure.*

(2) A liquid does not get hotter as it continues to boil. Water boiling vigorously has the same temperature as water boiling slowly. Thus we find that *the boiling point of a pure liquid does not change, but remains constant until all the liquid has vaporized.*

(3) From what we learned in the preceding pages, we know that *the boiling point of a liquid rises as the atmospheric pressure increases, and falls as the pressure decreases.*

(4) Solids or gases dissolved in liquids change the boiling point of the liquids. Salt water boils at a higher temperature than fresh water. In general, *solids dissolved in liquids raise the boiling point. Gases dissolved in liquids usually lower the boiling point.*

(5) When two or more liquids having different boiling points are mixed, the mixture has a different boiling point. Generally, its boiling point is some temperature between the boiling points of the pure liquids. For example, water boils at 100° C., and alcohol at 78° C. A mixture of the two will usually boil at some temperature between 78° C. and 100° C.

How much heat is needed to vaporize one gram of water? Let us put a quart of ice water on a gas burner and find how long a time it takes to heat it to the boiling point. Of course, every gram of the water has absorbed 100 calories of heat in being warmed from 0° C. to 100° C. But if we continue to watch the time, we shall find that the water "boils away" slowly. In fact, it will take *more than five times as long* to change the boiling water into steam or vapor as it did to warm it up to its boiling point. All the time that the boiling water was being changed to steam, it was absorbing heat. Here again, the heat absorbed is latent (hidden), since it cannot be shown by a thermometer. We are thus led to believe that it takes more than 500 calories of heat to change one gram of boiling water into steam which has the same temperature. *The heat required to vaporize one gram of a substance without changing its temperature is called its heat of vaporization.*

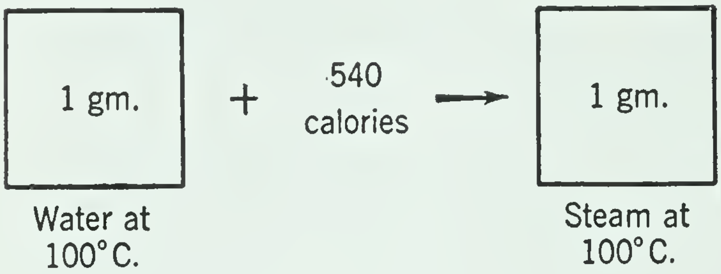


Fig. 11–9. Heat needed to vaporize one gram of water.

It is extremely difficult to measure the heat of vaporization of water accurately. The values generally accepted range from 535 to 540, with many authorities agreeing upon 539 as the most nearly accurate number. For solving problems, we shall use the number 540, since it simplifies multiplication, and is reasonably accurate. Hence, we conclude that *one must add to 1 gm. of boiling water at 100° C. 540 calories of heat to change it into steam at 100° C.* (See Fig. 11–9.) Then it will take 972 B.T.U.'s to change 1 lb. of boiling water at 212° F. into steam at the same temperature. To vaporize 1 gm. of alcohol, 205 calories are needed. The heat of vaporization of liquid ammonia is 295 calories. We shall see later that the high heat of vaporization of ammonia makes it useful in making artificial ice.

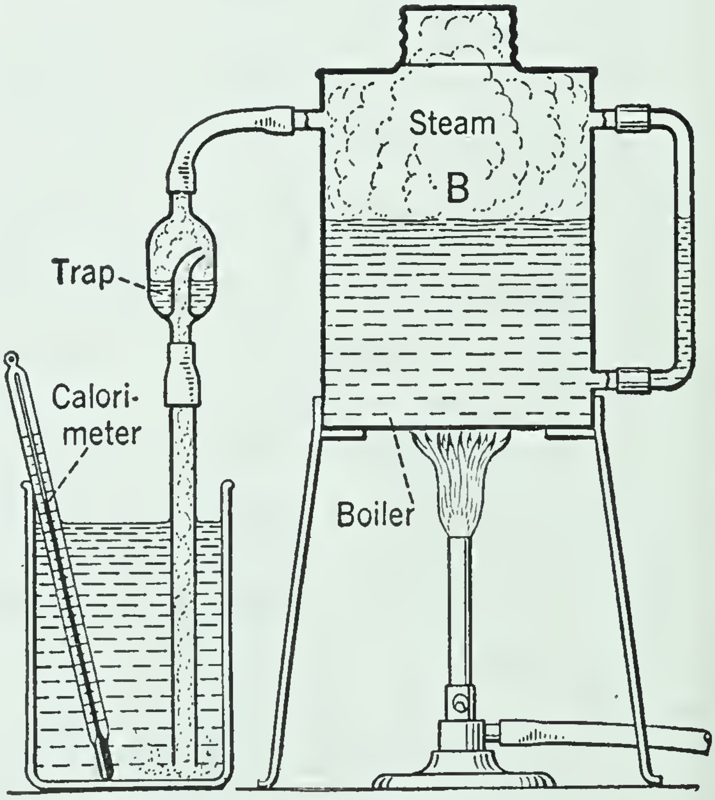


Fig. 11–10. How to find heat of vaporization.

How can heat of vaporization be found? Here, too, we use the method of mixtures. Steam is passed into cold water, as shown in Figure 11–10, and the increase in temperature is noted. The trap collects all the water formed from the steam which condenses before it passes into the calorimeter. One needs to know the weights of calorimeter, water, and steam. It is necessary, too, to know the original temperature of the steam and the water (and the calorimeter) as well as the final temperature of the mixture (and the calorimeter). Suppose that we get the following data:

Weight of calorimeter	120 gm.
Specific heat of calorimeter	0.1
Weight of water	402 gm.
Weight of steam	23.5 gm.
Initial temperature of the cold water	6° C.
Final temperature of water	40° C.
Temperature of steam	100° C.

Computations:

$120 \times (40 - 6) \times 0.1 = 408$ calories, absorbed by calorimeter.

$402 \times (40 - 6) \times 1.0 = 13{,}668$ calories, absorbed by water.

Total calories absorbed = 14,076.

When 23.5 gm. of steam condenses, 23.5 gm. of water at 100° C. are formed.

$23.5 \times (100 - 40) \times 1.00 = 1410$ calories, lost by water in cooling through 60° C.

$14{,}076 - 1410 = 12{,}666$ calories, lost by steam in condensing.

$12{,}666 \div 23.5 = 538.9$ calories, lost by 1 gm. of steam in condensing.

Demonstration. Make a trial determination of the heat of condensation or vaporization by following the experiment just outlined. Compare the result with the accepted value. What is the purpose of the water trap in Figure 11–10?

3. CONDENSATION

Water gives out heat as it condenses. We know that energy cannot be destroyed, and for that reason the heat that is absorbed during vaporization must be *set free* again during condensation. In the boiler of our furnace, the heat from the burning fuel changes the water into steam. The steam expands and rises to the radiators. There every gram of steam that condenses sets free the

540 calories which it had absorbed during vaporization. Thus heat is given out to the room by the radiators.

Every housewife knows that steam produces a much more severe burn than boiling water. Both may have the same temperature. But every gram of steam that condenses on a hand or arm sets free the 540 calories it had absorbed while it was being changed to vapor. After it has given up its 540 calories, each gram of steam can still liberate as much heat as a gram of boiling water.

4. APPLICATIONS OF BOILING AND CONDENSATION

How does the steam engine work? You have learned that a force is a push or a pull; that work is the result of a force exerted through a distance; that power is the rate of doing work; that energy is the ability to do work; and that heat is a form of energy. You have also seen that when water is changed into steam by heat, the expansion ratio is approximately 1 to 1700 under normal atmospheric pressure; and that if a gas is confined and heated the heat causes an increase in pressure (Charles' law). Now see how heat energy is converted into power by the steam engine.

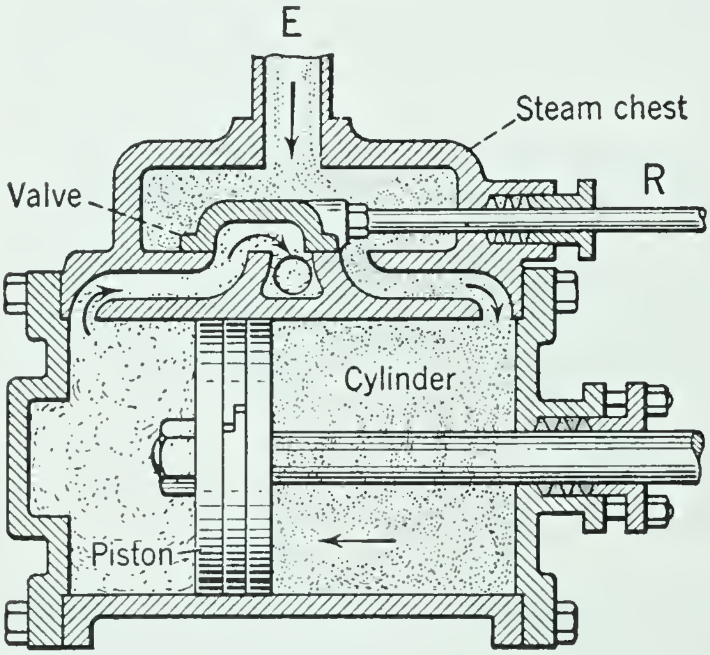


Fig. 11–11. Steam-engine cylinder and steam chest with slide valve.

What causes the reciprocating motion of the piston? From the boiler the steam is led to the steam chest through the pipe *E*, Figure 11–11. When the slide valve is in the position shown in the figure, the steam passes from the steam chest into the right end of the cylinder. Here it expands and pushes the piston with great force toward the left end of the cylinder. The spent steam from the previous stroke passes from the left end of the cylinder and out through the exhaust pipe. The path of the expanding steam is shown by the arrows.

The valve then slides to the right until the left end of the cylinder is connected with the steam chest, and the right end with the exhaust pipe. Steam enters the left end of the cylinder and pushes the piston to the right. By the movement of the valve, steam is admitted alternately to the ends of the cylinder. Thus the piston is pushed to and fro alternately. Such a motion is called a *reciprocating* motion. The student should observe that the openings in the cylinder are connected alternately with the steam chest and the exhaust by means of the sliding valve.

How does the piston turn the drive wheel or the belt wheel? The motion of the piston is reciprocating, or to-and-fro. If it is to drive the wheels of a locomotive or turn the belt wheel of a piece of machinery, it is necessary to change the to-and-fro motion into a rotary one. (See Fig. 3–16, the treadle of the sewing machine.)

In Figure 11–12 one end of the piston rod *A* is fastened to the end of the connecting rod *S*. The other end of the connecting rod is attached to the crank *F* at the end of the crankshaft *O* by means of a collar. While the piston in the cylinder (not shown in figure) moves to the right the length of the cylinder, the point

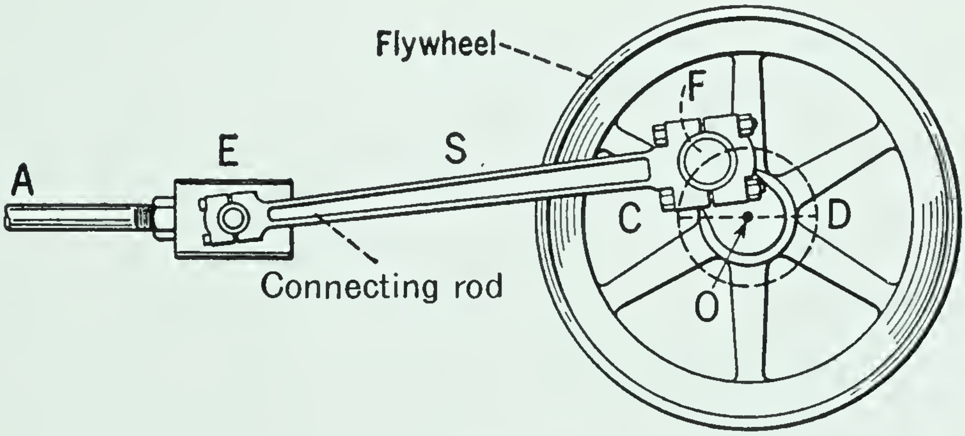


FIG. 11–12. Reciprocating motion is changed to rotary motion.

E moves to the right a distance equal to the diameter *CD* of the circle described by the crankpin *F*. Of course, the crankpin moves along the half-circumference from *C* to *D*. During the return stroke of the piston, the point *E* moves to the left and pulls the crankpin *F* around the other half-circumference from *D* to *C*. The inertia of the heavy flywheel carries the piston past the two points where there is no steam pressure, or past the two positions known as "dead centers."

How are the valves controlled? (1) *Slide valves.* It is important to remember that the slide valve must open and close the pipes leading from the steam chest to the different ends of the cylinder at exactly the right time. These pipes make connections, too, between the ends of the cylinder and the exhaust pipe. The rod *R* of Figure 11–11 is connected by means of shaft *A*, Figure 11–13, to an eccentric controlled by the crankshaft upon which the flywheel turns. The shaft, *A*, ends in a collar which fits around the disc, *D*. This disc rotates about the center, *C*, an axis which is off center (eccentric). During one-half a revolution, the point *X* moves along the curve as indicated by the arrows, and the end, *A*, of the shaft or rod moves to the left and slides the valve to the left in the steam chest. As the revolution is completed, the end of the shaft is pulled an equal distance to the right. While the point *X* describes a complete circle, point *A* moves backward and forward, controlling the movement of the valve at the same time.

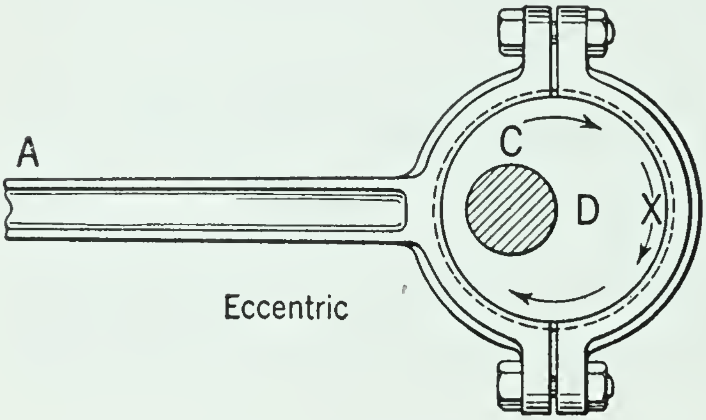


FIG. 11–13. An eccentric is used to control a slide valve.

(2) *Corliss valves.* These valves, which are used in some large steam engines, do not slide back and forth, but they open and close by rocking or turning slightly in the valve seats. These valves are automatically rotated by a complicated system of levers driven by eccentrics on the engine shaft. This type of

valve eliminates the steam chest which reduces heat loss by radiation. (See Fig. 11–14.) Each of the four valves may be timed independently of the others, thus making greater efficiency possible.

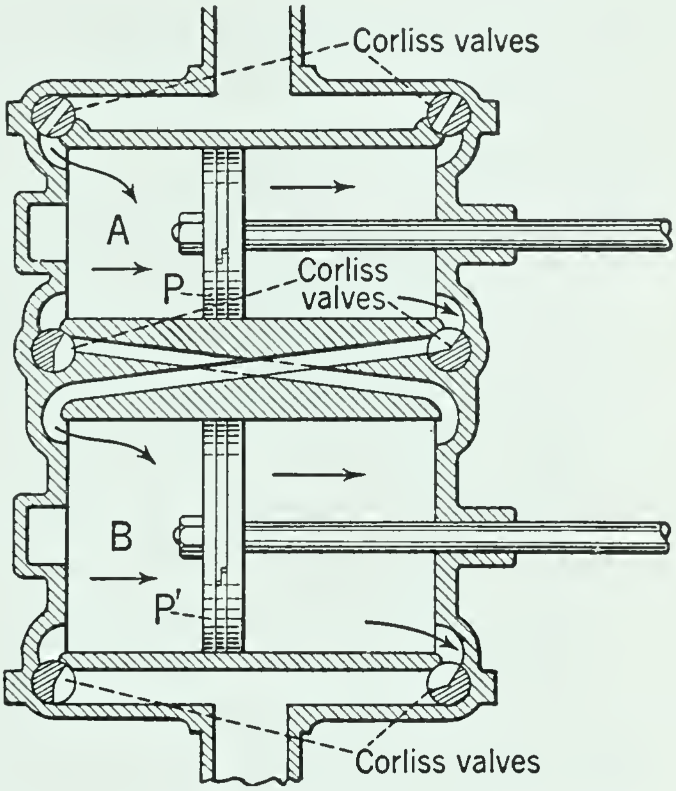


Fig. 11–14. A double-expansion engine.

There are two types of steam engines. (1) *Noncondensing engines.* Suppose the steam as it comes from the steam chest into the cylinder is under a pressure of 85 lb. per sq. in. It presses against every square inch of the piston with that force as it pushes the piston along the cylinder. But the spent steam on the opposite side of the piston is meeting a backward pressure of one atmosphere, or nearly 15 lb. per sq. in., as it is escaping into the air. Such back pressure reduces the *effective steam pressure* to only 70 lb. per sq. in. To get an effective pressure of 85 lb. per sq. in. with such an engine, the pressure in the steam chest must be equal to 100 lb. per sq. in. A steam engine of this type is called a *high-pressure engine* or a *noncondensing engine.*

(2) *Condensing engines.* Many stationary engines are fitted with a condenser, in which the spent steam is condensed by means of a spray of cold water. Thus a partial vacuum is formed in the condenser, and the backward pressure of the air against the escaping steam is much reduced, possibly to only 1 lb. per sq. in. If an engine is fitted with such a condenser, a boiler pressure of 86 lb. per sq. in. is approximately as effective as a boiler pressure of 100 lb. per sq. in. when used with a noncondensing engine. *Condensing engines* are sometimes called *low-pressure engines.* Of course, a condenser adds to the weight of the engine.

What is a compound engine? Many locomotive engines are of the high-pressure, noncondensing type. To increase efficiency, *compound engines* are used. (See Fig. 11–14.) When the steam leaves the first cylinder, it still has much expansive force. Hence it is led to a second cylinder, where it does useful work by expanding against a larger piston, P'. An engine of this type is called a *double-expansion engine.* *Triple-expansion* and even *quadruple-expansion engines* are sometimes used.

How is boiler efficiency provided? An ordinary wash boiler heated over a gas range produces steam, but the volume of steam produced is very low because there is so little surface exposed to the flame compared to the volume of water. The manufacturer of boilers for generating steam so designs them that the fire and flames will come into contact with the largest possible heating surface. Two types are in use:

(1) *Water-tube type.* Such a boiler is often used with stationary engines. The flames play all around a number of pipes filled with water and also against the bottom of the boiler itself. (See Fig. 11–15.) More heat is absorbed in this way. Some automatic stokers are of the underfeed type and some are an endless screw.

(2) *Fire-tube type.* This type of boiler is used on locomotives. From the firebox the flames are drawn through long horizontal tubes which are surrounded with water. The exhaust steam escapes through the smokestack and produces the draft.

How do engineers save fuel? In the diagram, Figure 11–15, we see that *baffle walls* are used to prevent the flames and hot gases from going directly up the chimney. They are forced to take a circuitous path which enables the water to absorb more of the heat before they reach the stack. The automatic stoker feeds the coal to the fire just as fast as it is burned, thus insuring complete combustion. An additional supply of hot air is fed into the flames, too, to aid in making the combustion more complete.

The exhaust steam is often used to preheat the water before it goes into the boiler. Such an arrangement is called a *feed water heater.* It is also possible to use an *economizer,* which uses the heat from the waste fuel gases to preheat the water.

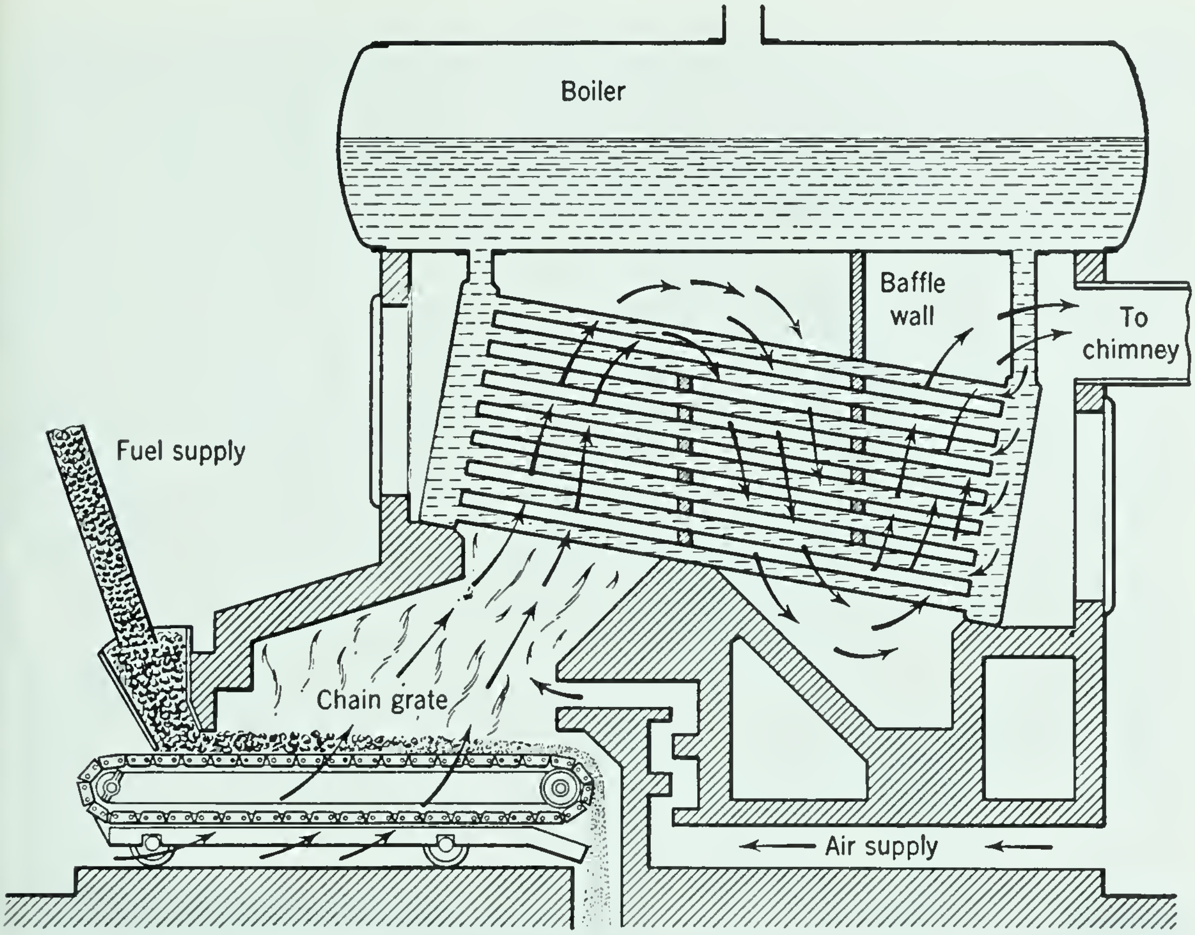


FIG. 11–15. The automatic stoker saves fuel and eliminates smoke.

How does the steam turbine work? The wind blowing against the blades of a windmill drives the wheel. The water acting against the blades of a water turbine drives the turbine. Steam, too, can be directed upon the blades of a turbine to make it rotate rapidly. The different types of turbines differ mainly in the manner in which the steam is directed against the blades. In the Curtis turbine, the steam is directed through nozzles set at such an angle that as soon as the steam strikes the blades of the turbine it is deflected to the opposite side of the wheel. (See Fig. 11–16.)

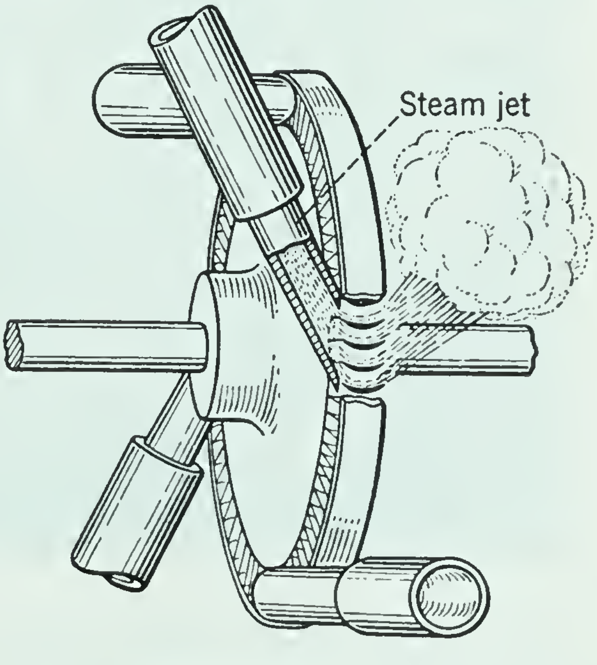


FIG. 11–16. The turbine principle.

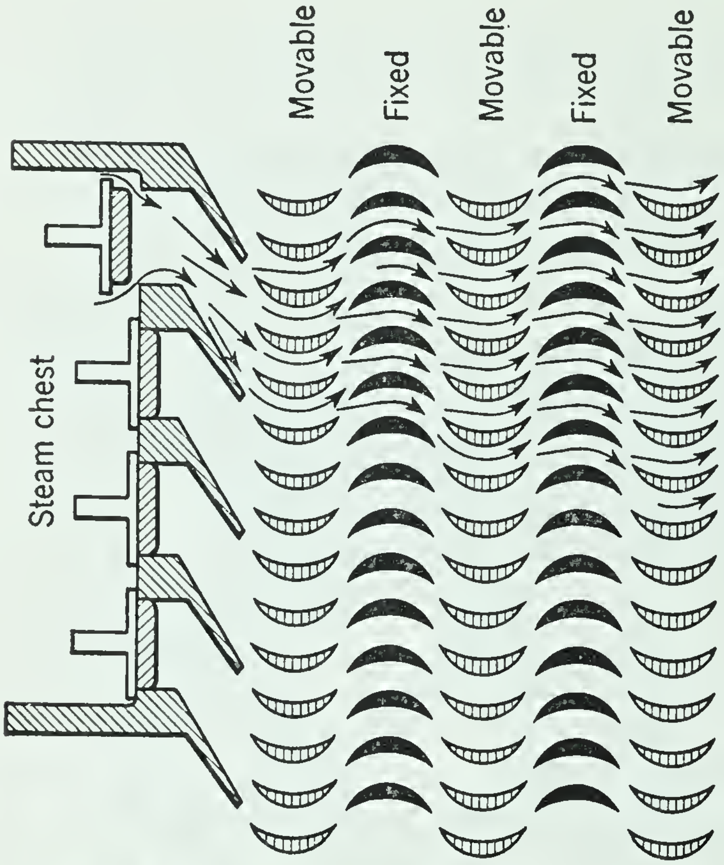
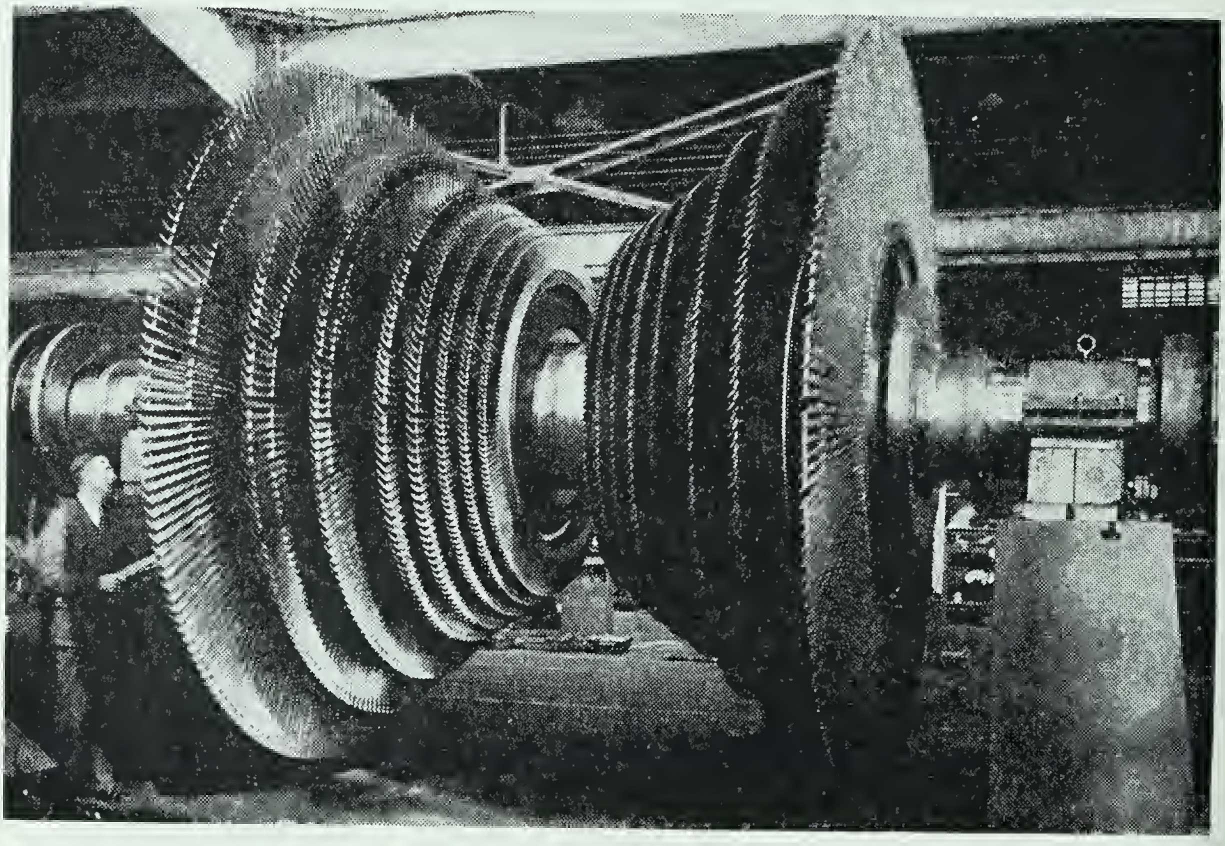
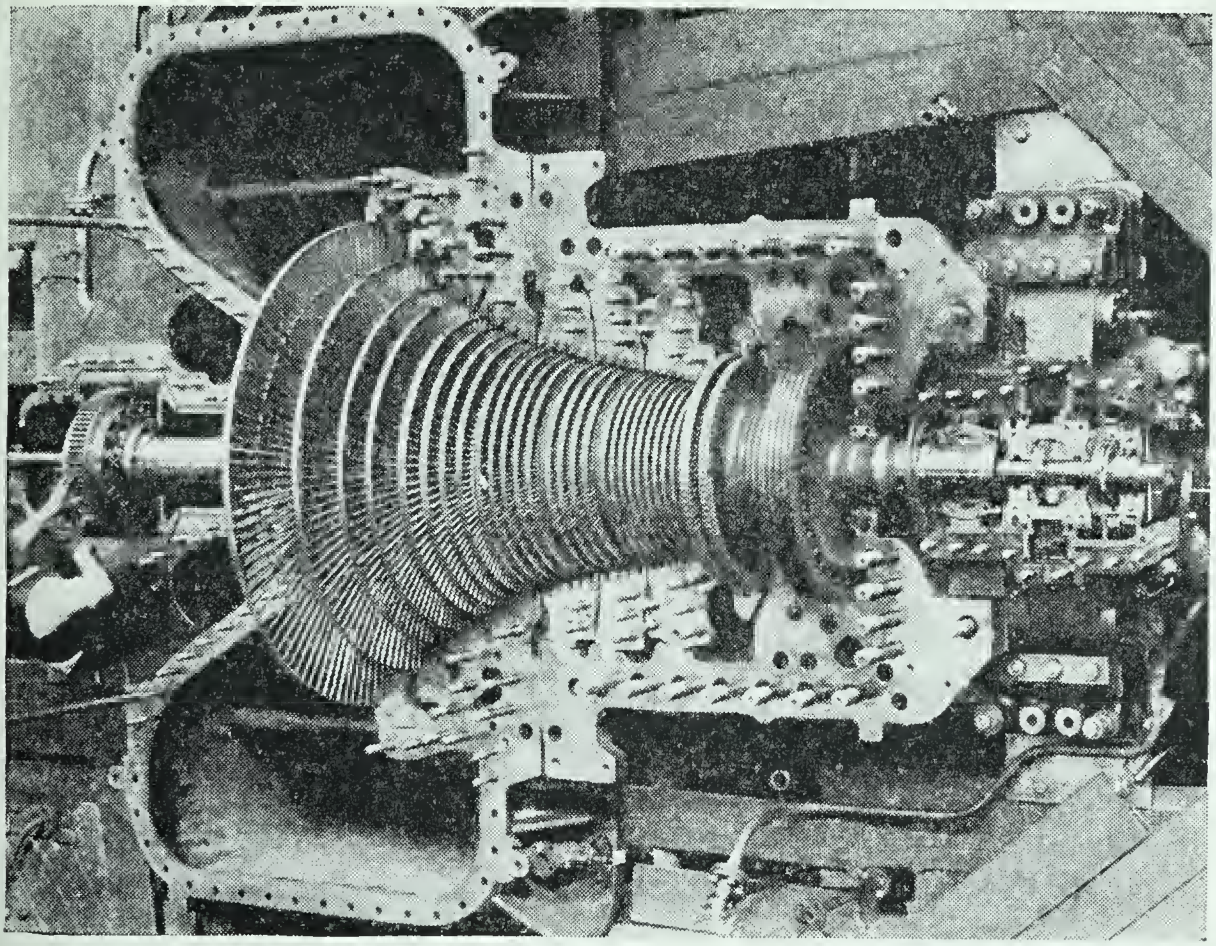


FIG. 11–17. Path of steam through a Curtis turbine.



Courtesy of Westinghouse

FIG. 11–18. Rotor of Westinghouse steam turbine. There are 1500 blades on this rotor. The longest blades are 38 inches in length, and move with a tip speed of 13 miles per minute, nearly as fast as a bullet.



Courtesy of Westinghouse

FIG. 11–19. Stator base and rotor of Westinghouse turbine. (20,000 kilowatt.) Tips of the longest blades move 1259 ft. per sec., faster than the velocity of sound.

From the first set of movable blades, the steam passes to a set of fixed blades, so curved as to direct the steam against another set of movable blades. (See Fig. 11–17.) In this manner the steam passes from a set of movable blades to a set of fixed blades, and so on, until its expansive force is practically spent.

The Parsons and Westinghouse turbines consist of a cylindrical drum, or *rotor*, having a large number of blades set much like the blades of a windmill. (See Fig. 11–18.) The rotor is mounted in a *stator* (stationary) base or casing which has a large number of fixed blades, as shown in Figure 11–19. The steam enters near one end of the turbine and flows along the space between the casing and the rotor, exerting its expansive force against the rotor blades and causing the rotor to spin rapidly. The diameters of both the rotor and casing are made larger near the outlet end to utilize more fully the expansive force of the steam.

Steam turbine versus reciprocating steam engine. On ocean liners, fast cruisers, and destroyers, the steam turbine is in common use. It has a decided advantage when high speed is desirable. For a given horsepower, the steam turbine occupies less space than a reciprocating engine. The rotary motion of the turbine causes much less vibration than the to-and-fro motion of the reciprocating engine. The steam turbine is more efficient when running at high speed. The rotor of the turbine may have the same shaft as the electric generator which it drives, thus making the transmission of power simple.

The steam turbine is not so efficient at low speed as the reciprocating engine, because the steam travels through the turbine at high velocity and much of its expansive force is lost when the speed is reduced. The reciprocating engine may be easily reversed, but the direction of the steam turbine cannot be reversed.

Cooling Systems. The cooling system of early types of internal-combustion engines was very simple. The single cylinder of stationary gasoline engines was surrounded by water in an open container. When the water reached the boiling point, further removal of heat from the cylinder was accomplished by changing some of the water to steam, which escaped. We have already learned that one pound of boiling water will absorb 972 B.T.U.'s. This evaporating cooling system required less water to be circulated than would have been necessary if the cylinder temperature had been kept below the boiling point of water.

A modification of the simple evaporative cooling system has been used to a limited extent in multicylinder engines. The steam formed by the evaporation of water surrounding the cylinders in the engine block flows into the radiator, where it is condensed. From the radiator, the condensed water is pumped into the engine block. Although this vapor or steam cooling system maintains a high uniform cylinder temperature, and requires a comparatively small volume of water, its several complications have prevented its use in automobile engines.

Why does evaporation produce a cooling effect? If we wet one hand and then step out-of-doors on a cold day in winter, the hand that was wet will be decidedly colder than the other. Every gram of water that evaporates takes 540 calories of heat from the skin. Such subtraction of heat must cause a cooling effect. The skin is a delicate *thermostat.* We perspire when we get too warm. If the perspiration evaporates, the skin is cooled. If we sit in a breeze where the perspiration evaporates more rapidly, we are cooled more decidedly. If the air is very humid on a hot day, we suffer from the heat because the perspiration does not evaporate and cool us. Alcohol is used for a sponge bath to reduce fever. It evaporates faster than water and cools the skin more. Ether boils at about 35° C. It evaporates so fast when poured on the hand that it makes the hand feel very cold.

Our streets are sprinkled in hot weather. The heat needed to vaporize the water comes from the hot pavement and the surrounding air, and both are cooled.

Let us put a few drops of water on a wooden block, place a watch glass convex side down in the water, and pour two teaspoonfuls of ether onto the watch glass. If we put the whole apparatus under a bell glass and exhaust the air from the bell glass rapidly, the ether will boil away quickly under the reduced pressure. The rapid evaporation of the ether will take heat from the thin film of water under the watch glass so rapidly that the water will freeze. At the end of the experiment we shall find the watch glass frozen to the wooden block.

What principle is used in making ice? On a small scale, ice was formed in the experiment just described. To make ice commercially, one depends upon the *cooling effect of evaporation.* The faster the evaporation, the greater the cooling effect. Ether produces a greater cooling effect than alcohol, and alcohol a greater cooling effect than water. Suppose we use a liquid which boils at − 34° C. Then the cooling effect becomes intense.

At room temperature, ammonia is a light gas, but it can be converted into a liquid by compressing it and cooling it at the same time. When it evaporates, every gram of it absorbs about 295 calories of heat from the medium which is in contact with it.

Let us study Figure 11–20. Ammonia gas is compressed in the cylinder by the piston. The heat of compression is absorbed by the cold water which flows down over the cooling coils, and the ammonia liquefies. As the liquid ammonia flows through the expansion valve into the coils of the brine tank, it evaporates and expands. Both the evaporation and the expansion produce a cooling effect, and the brine which surrounds the coils is cooled, possibly to − 10° C. or lower. The cans of fresh water which are immersed in the brine are frozen into cakes of solid ice in from 24 to 48 hours.

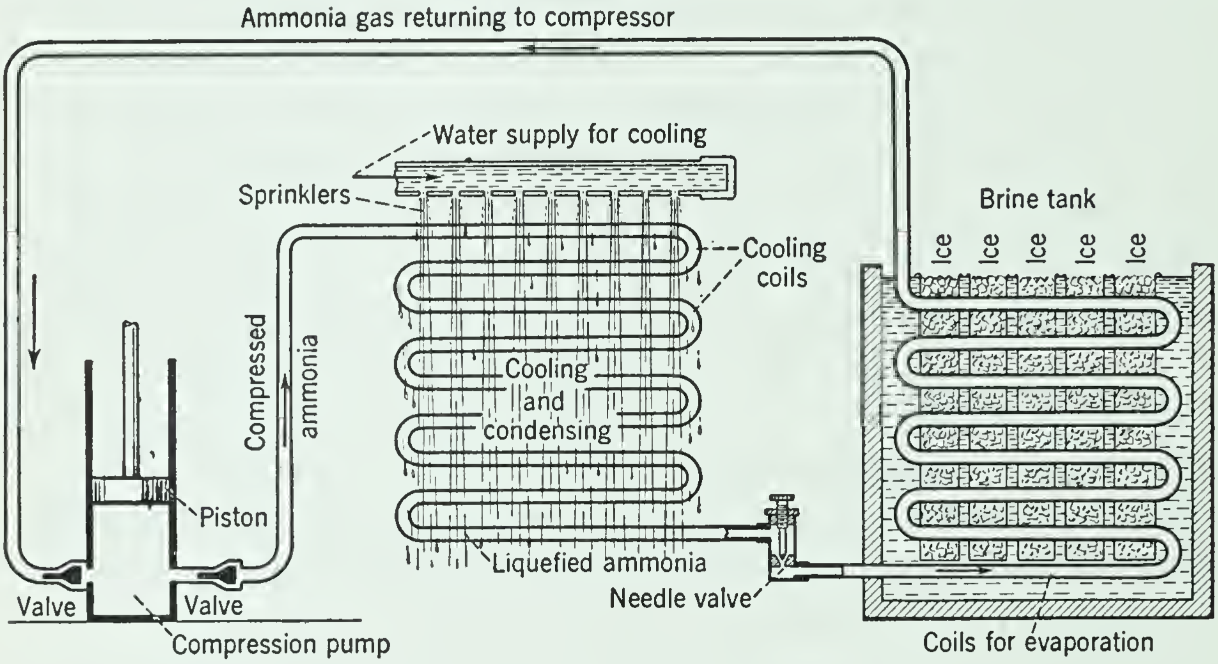


FIG. 11–20. Diagram of a plant for making ice.

In cold storage plants, the cold brine is pumped through pipes in storage rooms. Just as hot water flowing through a radiator warms a room by radiation, so cold brine circulating through coils of pipe will cool a room to any desired temperature.

How does the mechanical refrigerator work? *Electric type.* In many houses and apartment houses, electricity is now used to make ice and to keep refrigerators cool. A small electric motor of about one-sixth horsepower is used to operate a small compressor. The gas used may be sulfur dioxide, because it is so easily liquefied.

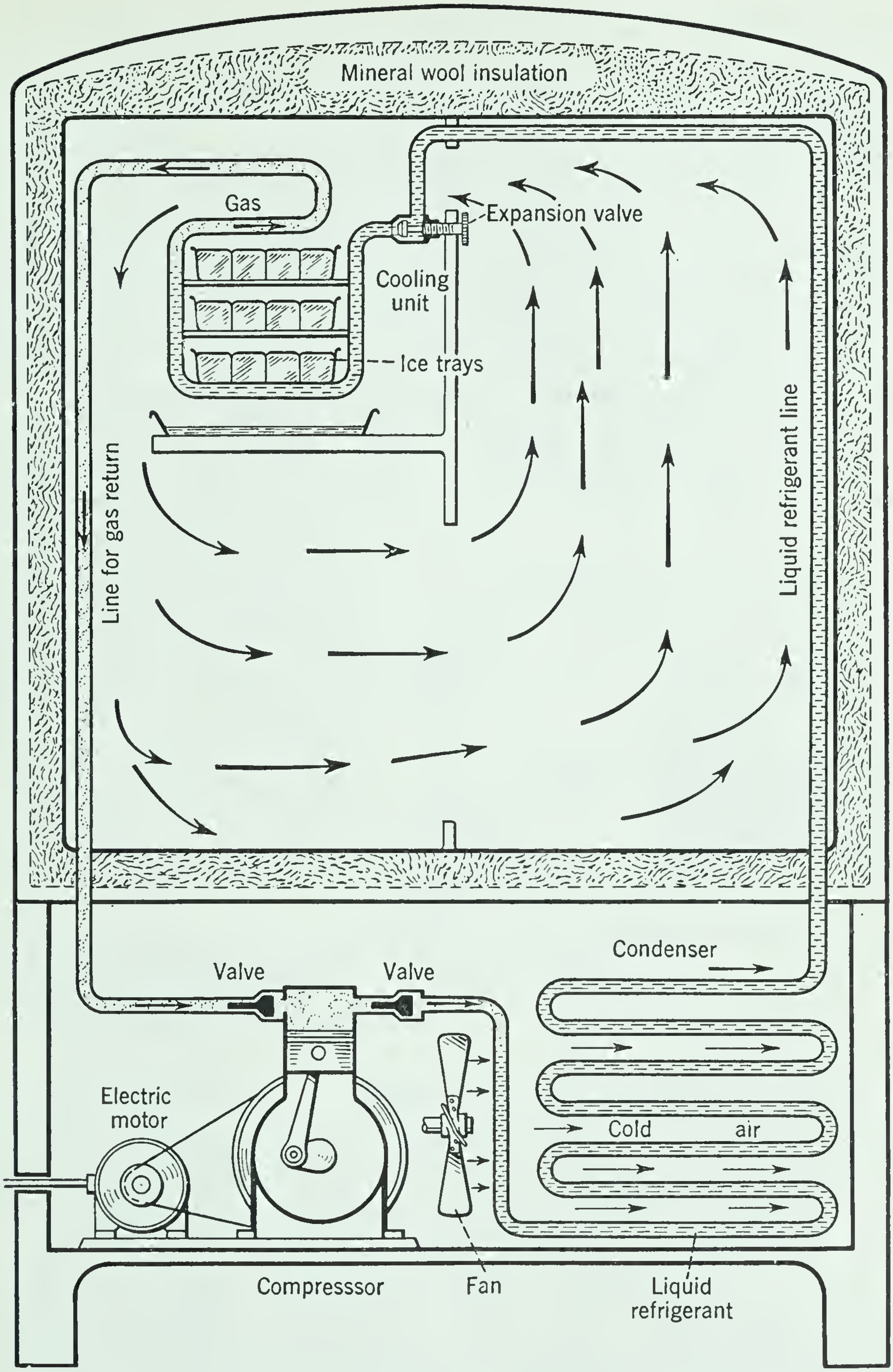


FIG. 11–21. A mechanical refrigerator. The compressor is driven by a small electric motor. Air is blown over the cooling coils by a revolving fan. The heat to evaporate the refrigerant is taken from the water in the trays. Subtracting heat from water will eventually cause it to freeze.

In many of the new refrigerators methyl chloride or di-chloro-di-fluoro methane is now used. (See Fig. 11–21.) Air circulates freely around the coils to absorb the heat produced by compressing the gas. Then the liquid refrigerant is led to the coils in one compartment of the refrigerator. As it evaporates in these coils, it absorbs heat from the surrounding air, thus cooling the refrigerator compartments and the food in them. Pans of water placed inside the coils are converted into ice as the heat from the water, too, is absorbed during the evaporation of the refrigerant.

Gas type. Michael Faraday devised an ingenious method of liquefying gases. A thick-walled tube of the type shown in Figure 11–22 was filled with chlorine gas. One end of the tube was packed in a freezing mixture of salt and ice, while the other end was being heated. Heating one end of the tube *compressed* the gas in the other end, where it was liquefied as the freezing mixture cooled it. By a similar method of compressing gases by heating them in a confined space and then cooling them, Faraday liquefied several different gases.

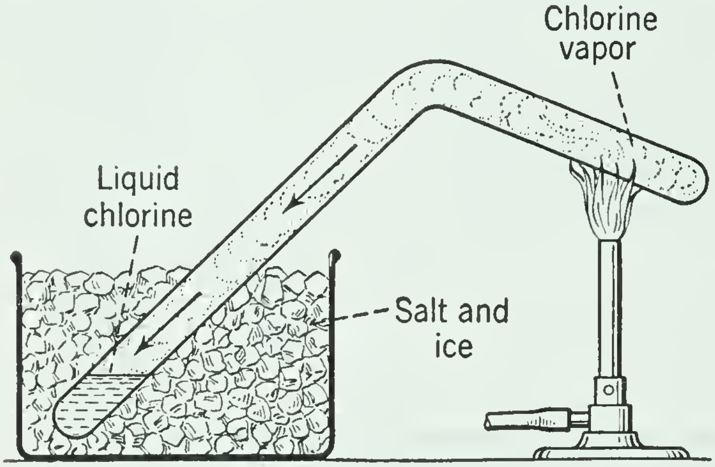


Fig. 11–22. In such a tube Faraday succeeded in liquefying several different gases.

Water, ammonia gas, and hydrogen are placed in a series of pipes and sealed. Ammonia gas is extremely soluble in water, but it is driven out of the water by the heat of a gas flame. The rapid expulsion of the ammonia gas from the water *compresses* it until it liquefies upon being simultaneously cooled. Methyl chloride is used to circulate around the pipes where compression is taking place and to cool the ammonia by absorbing its heat of compression. The liquid ammonia evaporates and expands inside the coils in the refrigerator compartment, thus producing the cooling effect. The ammonia then redissolves in the water.

The hydrogen prevents the formation of a vacuum by the rapid solution of the ammonia gas, and thus prevents "pounding." The process is repeated continually. The gas refrigerator is silent in its operation, since there are no moving parts.

How are gases liquefied? Faraday made a list of several *fixed* gases, as he called them, because he could not liquefy them by the method described in the preceding section. Such gases as hydrogen, oxygen, and air, for example, cannot be liquefied by pressure alone. It is necessary to cool air to − 140° C. before it can be liquefied by any pressure, however great. The temperature to which any gas must be cooled before it can be liquefied by pressure is called its *critical temperature.*

The pressure needed to liquefy a gas at its critical temperature is called its *critical pressure.* All gases have now been liquefied, by subjecting them to high pressure, and then cooling them by expansion. Successive compressions and coolings are necessary in the case of those gases that have very low boiling points.

How is liquid air made? In an apparatus of the type shown in Figure 11–23, air is first compressed. Then it circulates through

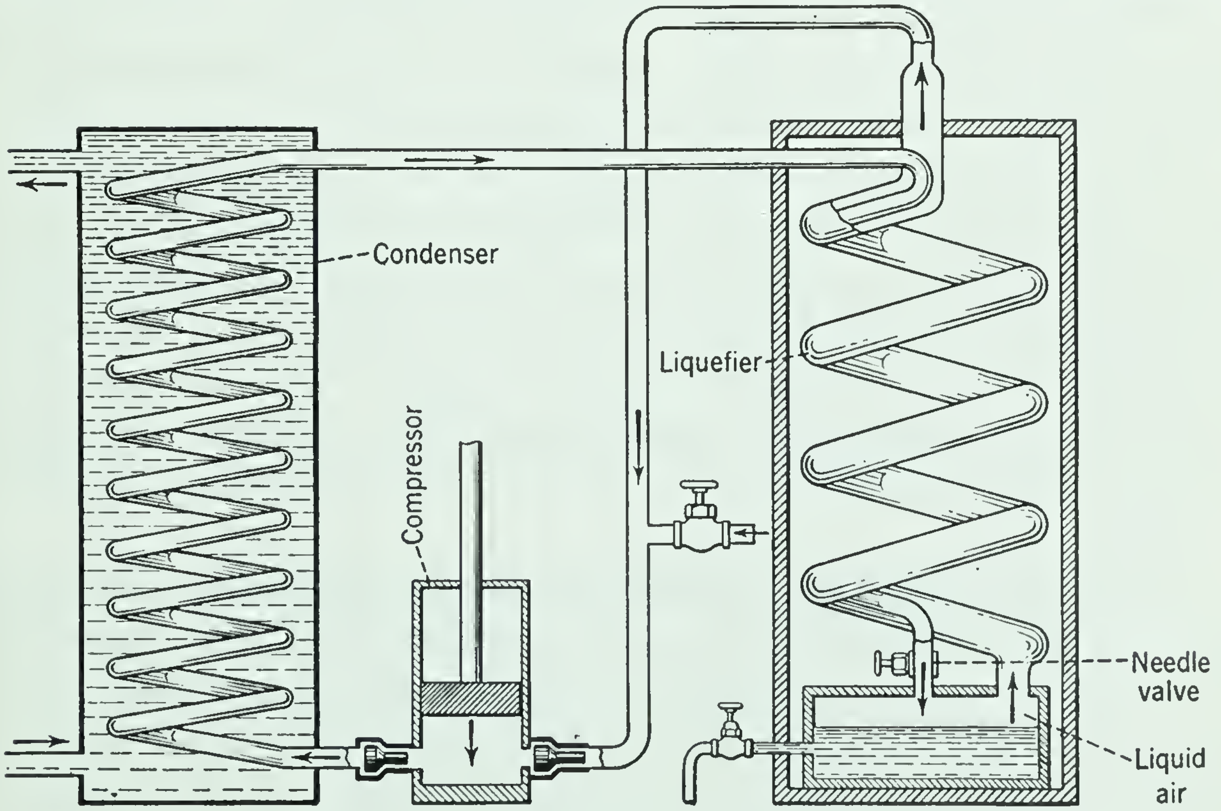


FIG. 11–23. One type of apparatus that may be used for liquefying air.

the cooling coils where the heat of compression is absorbed. It expands rapidly as it escapes through the needle valve and it is thus further cooled. It cools the air in the inner concentric coils as it returns through the outer coils to the compressor. By continually compressing the air, absorbing the heat of compression, and then letting it expand, some of the air at the end of the concentric coils is finally cooled to its critical temperature, and changes into a liquid.

Liquid air under atmospheric pressure boils at from – 182° C. to – 194° C., the variation depending upon the per cent of nitrogen present. Liquid hydrogen boils at – 253° C. If we throw a piece of ice into a vessel of liquid air, it will probably boil over. The ice is so hot compared to the liquid air that it makes it boil vigorously. Boiling water is only 100 Centigrade degrees hotter than ice, but ice is more than 180 Centigrade degrees hotter than liquid air. Rubber tubing immersed in liquid air soon becomes hard and brittle. It can be easily broken by hitting it with a hammer. Mercury and alcohol may be frozen solid by pouring liquid air over them. In an open vessel standing on a cake of ice, liquid air will boil vigorously. It may be kept for a few hours in an unstoppered Dewar flask, which is a double-walled vacuum flask similar in construction to a thermos bottle.

Some gases that are easily liquefied are now marketed in liquid form after being forced into strong steel cylinders under high pressure. Carbon dioxide in liquid form is now marketed, and it is also sold in the solid state for use as a refrigerant. Because it sublimes, one manufacturer uses the name "Dry ice" for his product. It takes only a small quantity to produce the same cooling effect as a large piece of ice, since its temperature is about – 80° C.

The effect of heat on water can be shown graphically. Suppose that we plot a curve to show what changes take place when ice at – 10° C. is heated until it is all converted into steam under pressure at 120° C. (See Fig. 11–24.) Since the specific heat of ice is 0.5, 1 gm. of ice absorbs 5 calories in being warmed to zero degrees; 80 calories are absorbed in melting the ice. *Note that* *there is no temperature change;* 100 additional calories are needed to warm the water to the boiling point. Another change of state occurs, in which 540 calories of heat are absorbed. If the steam, which has a specific heat of almost 0.5, is under pressure, 10 calories will be used to heat 1 gm. from 100° C. to 120° C. The student will find this curve helpful in solving problems involving specific heat, heat of fusion, and heat of vaporization. We see that it needs 720 calories of heat to change 1 gm. of ice at 0° C. into 1 gm. of steam at 100° C.

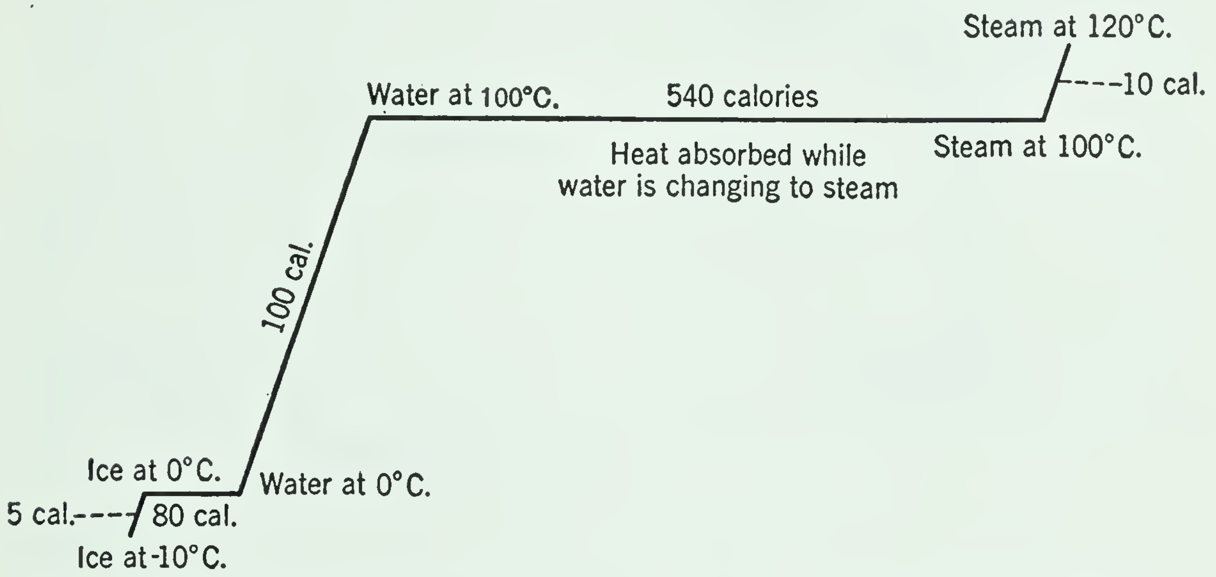


FIG. 11–24. Heat absorbed during a change of state and temperature.

What is distillation? For some purposes it is desirable to have water which is free from mineral matter. No impurities *dissolved* in water can be removed by filtering. If we vaporize the water, the mineral matter that had been dissolved remains behind, and the pure water vapor can then be condensed. An apparatus convenient for this process, which is called *distillation,* is shown in Figure 11–25. The distilling flask contains the impure water. As it boils, the vapor passes through the inner tube of the condenser, and is cooled by the cold water which flows through the outer tube. Distilled water is used in storage batteries for automobiles and in making up many solutions in chemical laboratories.

The pupil must not get the idea that distillation merely means purifying water. Many liquids are distilled to purify them. It is

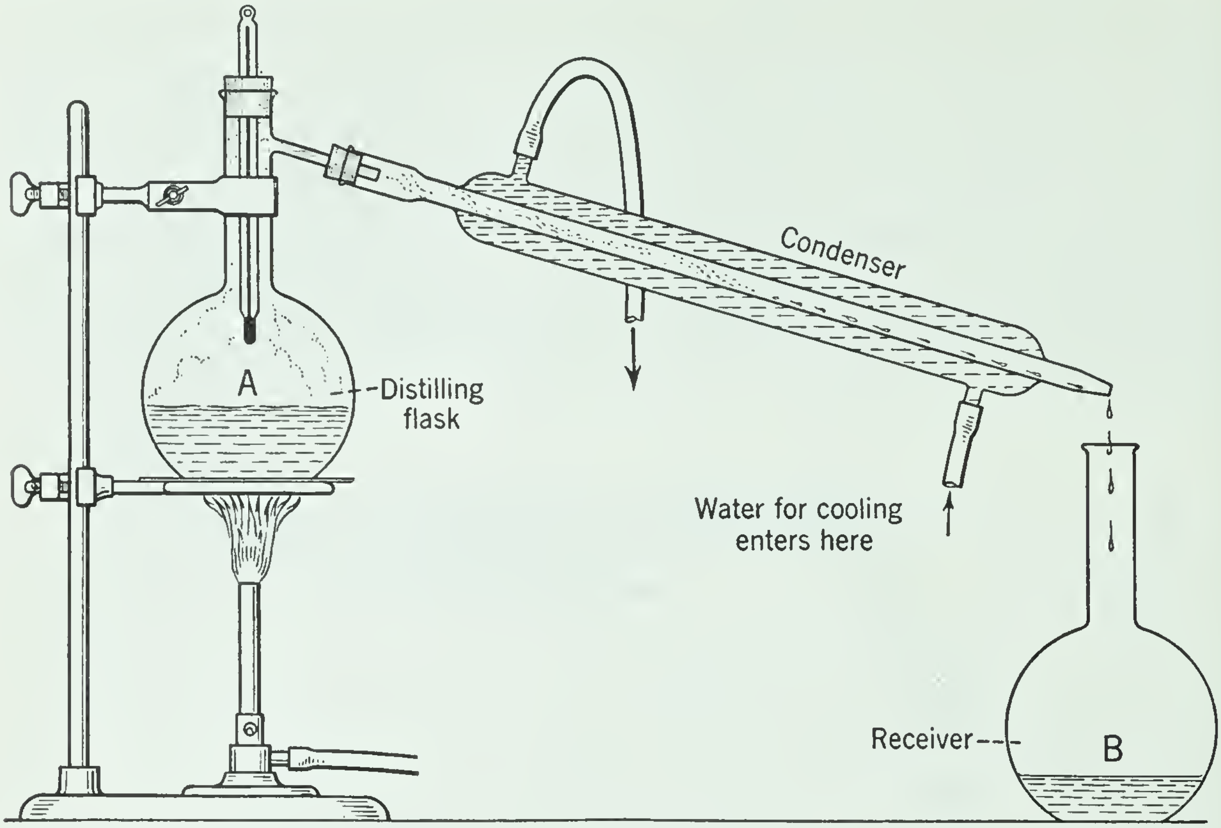


Fig. 11–25. Purification by distillation.

really *a complex process which consists in first vaporizing a liquid and then condensing its vapor.* Dew is distilled water.

What is meant by fractional distillation? Possibly you know someone who puts alcohol in the radiator of his car in winter as an antifreeze. The boiling point of such alcohol is about 80° C. and that of the water with which it is mixed is about 100° C. When the engine gets warm, the alcohol vaporizes faster than the water does. In other words, one fraction of the liquid distils off faster than the other fraction. It is possible to separate two or more liquids which have different boiling points by distilling off one portion and collecting it, then raising the temperature and distilling off a second portion.

Petroleum, or crude oil, is a mixture of a number of liquids which have different boiling points. Some of the most important products obtained from petroleum are gasoline, kerosene, lubricating oils, fuel oils, petroleum jelly, and paraffin. When petroleum is heated in a huge distilling flask, the products which have low boiling points boil off first, followed in order by those of increasingly higher boiling points. The process of separating such a mixture is called *fractional distillation.* Figure 13–24 shows a *still* and *fractionating column* used in the refining of petroleum.

Some complex solids, such as wood and coal, yield many different products when they are *dry* distilled. The solid is put in a large retort and strongly heated. Some of the products which escape are gaseous, some of them are liquid, and some of the residues left in the retort are solid. This process is called *destructive distillation.*

Demonstration. By means of the apparatus shown in Figure 11–25, illustrate fractional distillation. Place in flask *A* equal volumes of water and alcohol. Heat the mixture and note the temperature at which it begins to boil. Regulate the flame so that slow boiling continues to take place. As soon as about 10 cc. of distillate have been collected in receiver *B*, replace *B* with a clean dry flask. Repeat until four or five samples or fractions have been collected. Note the odor of each fraction. Is the alcohol content the same in each? Did the temperature remain constant during the collection of the fractions?

SUMMARY

1. Fusion is the process of changing from the solid to the liquid state. The temperature at which the change occurs is the melting point. Increase in pressure raises the melting point of substances that contract when solidifying, and lowers the melting point of substances that expand during solidification.

2. To change 1 gm. of ice at 0° C. to water at the same temperature requires 80 calories; the same amount of heat is lost when 1 gm. of water freezes.

3. The boiling point of a liquid may be defined as the temperature at which the pressure of its vapor equals the atmospheric pressure. An increase in pressure raises the boiling point; a decrease in pressure lowers the boiling point.

4. Distillation, a process consisting of evaporation and condensation, is used to purify substances or to separate liquids having different boiling points.

5. To change 1 gm. of water at 100° C. into 1 gm. of steam at

the same temperature requires 540 calories; the same amount of heat is set free when the steam condenses.

6. Evaporation requires heat. This heat is taken from the surrounding medium, thus lowering its temperature. Artificial ice is made by the application of this principle.

7. The steam engine and the steam turbine use boiling and condensation in changing heat energy into mechanical energy.

How many of the following terms can you define or explain?

Fusion
Solidification
Liquefaction
Melting point
Freezing point
Noncrystalline
Welding
Alloy
Sublimation
Heat of fusion
Evaporation
Condensation
Boiling
Heat of vaporization
Distillation
Fractional distillation
Critical temperature
Critical pressure

SELF-TESTING EXERCISES

ANSWER THESE QUESTIONS

On a separate sheet of paper numbered from 1 to 8 write the letters for the phrases that answer the following questions correctly.

1. What do crystalline solids tend to do in changing from the liquid to the solid state? (*a*) Expand; (*b*) contract; (*c*) remain at constant volume.

2. What is the correct name for the process of freezing again after pressure is released when melting has been caused by pressure? (*a*) Fusion; (*b*) solidification; (*c*) regelation.

3. Which of the following statements is true about heat of fusion? (*a*) It is the temperature at which a solid melts; (*b*) It is the heat necessary to vaporize one gram of a liquid; (*c*) It is the heat necessary to melt one gram of a solid without change in temperature.

4. Which of the following phrases correctly completes this statement? The rate of evaporation of a liquid increases with (*a*) An increase of pressure; (*b*) an increase in humidity; (*c*) an increase of surface area.

5. Which of the following phrases correctly completes this statement? The boiling point of a liquid decreases with (*a*) A decrease in pressure; (*b*) an increase in pressure; (*c*) a decrease in quantity of liquid.

6. Which of the following figures represents the correct heat of vaporization of water? (*a*) 80 calories; (*b*) 450 calories; (*c*) 540 calories; (*d*) 972 calories.

7. What is the correct expansion ratio when water is changed to steam under normal atmospheric pressure? (*a*) 1 to 2; (*b*) 1 to 100; (*c*) 1 to 1000; (*d*) 1 to 1700.

8. Which of the following phrases correctly completes the statement: The connecting rod and crank of a steam engine convert (*a*) Reciprocating motion into rotary motion; (*b*) to-and-fro motion into reciprocating motion; (*c*) heat energy into mechanical energy.

COMPLETE THESE STATEMENTS

On a separate sheet of paper numbered from 1 to 9 write the words needed to fill correctly the blank spaces in the following sentences.

Two pieces of wrought iron may be ..(1).. by heating them to white heat and pounding them together. An ..(2).. is a mixture of two or more metals melted together. The heat of fusion for ice is ..(3).. calories per gram. Commercial manufacture of ice depends upon the cooling effect of ..(4)... The temperature to which any gas must be cooled before it can be liquefied by pressure is called its ..(5)... A mixture of liquids may be separated by the process known as ..(6)... Solids dissolved in liquids ..(7).. the boiling point. Gases dissolved in liquids usually ..(8).. the boiling point. A substance is said to ..(9).. when it changes from a solid to a gas without appearing to liquefy.

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 8 write a T *or an* F *to show whether each statement is true or false.*

1. Boiling may be used as a means of cooling.
2. Some alloys are solid solutions of one metal in another.
3. Usually the freezing point and the melting point of a crystalline solid are the same.
4. When water freezes the surrounding atmosphere is cooled.
5. By means of reduced pressure water may be boiled at room temperature.
6. The fact that steam causes a more severe burn than boiling water proves that the steam has a higher temperature than boiling water.
7. Dry ice is ordinary ice which is full of unfrozen water.
8. When running at low speeds the steam turbine is more efficient than the reciprocating engine.

QUESTIONS

1. Which cools a refrigerator more, 1 lb. of ice or 1 lb. of ice water? Explain.

2. Explain how regelation helps in the movement of valley glaciers.

3. Why does snow "pack"? Why is it impossible to make snowballs if the temperature is much below 32° F.?

4. How would "flood conditions" be affected if the heat of fusion of ice were 10 instead of 80?

5. A spoonful of "water ice" seems much colder to the tongue than a spoonful of ice cream. Explain why. Do you think a thermometer would show any difference?

6. Why does salt thrown on icy sidewalks help to melt the ice?

7. For use in making type, would you use a metal that expands when solidifying, or one that contracts?

8. Why do streets dry so rapidly on a windy day?

9. Does fanning cool the face when one is not perspiring? Explain.

10. Food is sometimes kept in thick-walled porous vessels which have been immersed in water before using. Under what atmospheric conditions do you think such "iceless refrigerators" are fairly efficient?

11. Why is it difficult to keep cool in summer when the relative humidity is above 90%?

12. Is water any hotter when boiling vigorously in an open vessel than when boiling slowly? Try to find in the answer to this question a suggestion as to one method you can use for reducing your gas bills.

13. Why do clothes sometimes "freeze dry"?

14. Why does steam produce a more severe burn than boiling water at the same temperature?

15. The steam that enters a radiator may be the same temperature as the water that leaves it. How has the room been warmed?

16. Why do snow and ice melt so slowly in the spring, even when the temperature is considerably above the freezing point?

17. Why is it difficult to hard-boil eggs in an open vessel at the top of Pikes Peak?

18. Explain why sea water freezes less easily than fresh water.

19. What are the advantages of the pressure cooker?

20. Look up the meaning of the word *autoclave*. How is it like the pressure cooker? For what purpose is it used in biology and medicine?

21. The *olla* is an unglazed earthenware pot which finds use as a water bottle in hot countries. Explain how it can keep the water cool.

PROBLEMS

1. How many calories of heat do 25 gm. of steam lose upon condensing?

2. How many grams of water are formed when 25 gm. of steam condense? After 25 gm. of steam condense, how many additional calories will be lost when the resulting water cools to 50° C.?

3. How many calories are set free when 40 gm. of steam condense and then cool to 0° C.?

4. How many gm. of ice can be melted by 60 gm. of steam?

5. How many calories are lost by 80 gm. of steam in condensing, cooling to 0° C., and then changing to ice at 0° C.?

6. How many gm. of ice at 0° C. are needed to lower the temperature of 1000 gm. of water from 90° C. to 20° C.?

7. How many calories of heat are needed to warm 200 gm. of water from 20° C. to 100° C.? How many additional calories are needed to convert the water into steam?

8. A calorimeter weighing 200 gm. has a sp. ht. of 0.1. If its temperature is 20° C., how many grams of steam are needed to supply the heat needed to raise the temperature of the calorimeter to 90° C.?

9. A piece of iron weighing 200 gm. has a temperature of 200° C. It is added to 400 gm. of water at 20° C. If the final temperature of the mixture is 29° C., what is the sp. ht. of iron?

10. How many calories are needed to melt 200 gm. of ice? How many additional calories are required to warm the resulting ice water to 60° C.?

11. If 25 gm. of water at 80° C. are added to 25 gm. of ice at 0° C., how much water will be formed when the final temperature is reached, and what will be the final temperature?

12. How many B.T.U.'s are needed to melt 50 lb. of ice at 32° F.?

13. One lb. of ice is added to 10 lb. of water at 60° F. What will be the temperature of the mixture?

14. How many calories will be necessary to change 1 gm. of ice at 0° C. to steam at 100° C.?

XII

Proper Heat Transfer Is Essential in All Heat Engines

A. CONDUCTION

How is heat distributed? In an earlier chapter we learned that heat comes from the sun, from chemical action, and from wasted work. From the law of mixtures, we learned that heat can be transferred from one body to another. We want to know how heat gets from our furnaces in the basement to the rest of the house. If we learn how heat is distributed, we may be able to control such transfer of heat. In some cases we shall want to hasten the distribution of heat, and in other cases we shall attempt to prevent the escape of heat.

Physicists list three important ways in which heat is transferred from one place to another: *conduction*, *convection*, and *radiation.*

1. MOLECULAR COLLISION

How is heat conducted? If you let the bowl of your sterling-silver teaspoon stand in a cup of hot coffee, you would find the handle of the spoon hot enough to burn your fingers. When one end of a stove poker is held in some live coals, the other end of the poker will soon be too hot to be held comfortably. In some way, the heat is *conducted*, or *led*, from one end of each solid to the other end. The molecules of the live coals are in rapid vibration as they produce heat energy. The molecules of the poker which are adjacent to the coals receive some of this heat energy, which they transmit along the poker to other molecules.

Such transmission of heat from molecule to molecule is called conduction.

2. GOOD AND BAD CONDUCTORS OF HEAT

Some solids are better conductors of heat than others. From the preceding section we know that silver and iron are conductors of heat. By the use of a *conductometer*, the ability of solids to conduct heat may be compared. (See Fig. 12–1.) The rods are covered with paraffin or with a paint which changes color when heated. When steam is passed through the base of the apparatus, the *relative* conductivity of the metal rods can be determined by the rate at which the paraffin melts or the paint changes color. The order of conductivity of the five metals shown here is as follows: copper, aluminum, brass, iron, and German silver.

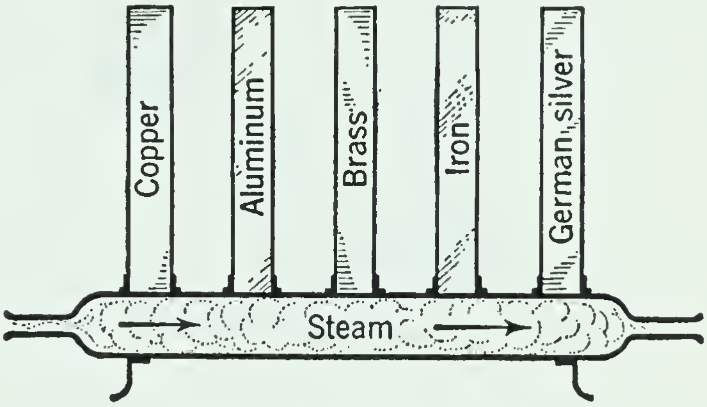


Fig. 12–1. Some metals conduct heat better than others.

Silver is the best conductor of heat known. Copper and aluminum are much better conductors than other common metals. German silver, which is an alloy of copper, zinc, and nickel, is not a particularly good conductor. Metals generally are much better conductors of heat than wood or stone. (See Table 9 of Appendix A.)

The fibers used for clothing are rather poor conductors, although linen and cotton are better than wool and silk. Sawdust is a poorer conductor of heat than wood, because there are so many air spaces between the particles. For the same reason, furs and feathers are poor conductors of heat compared to most solids.

Demonstration. Try the above conductivity experiment or compare the conductivity of copper with German silver by holding the ends of two equal lengths in a Bunsen flame. Which gets hot first?

Liquids are poor conductors of heat. Let us put a piece of ice in the bottom of a test tube, weight it, and then fill the tube two

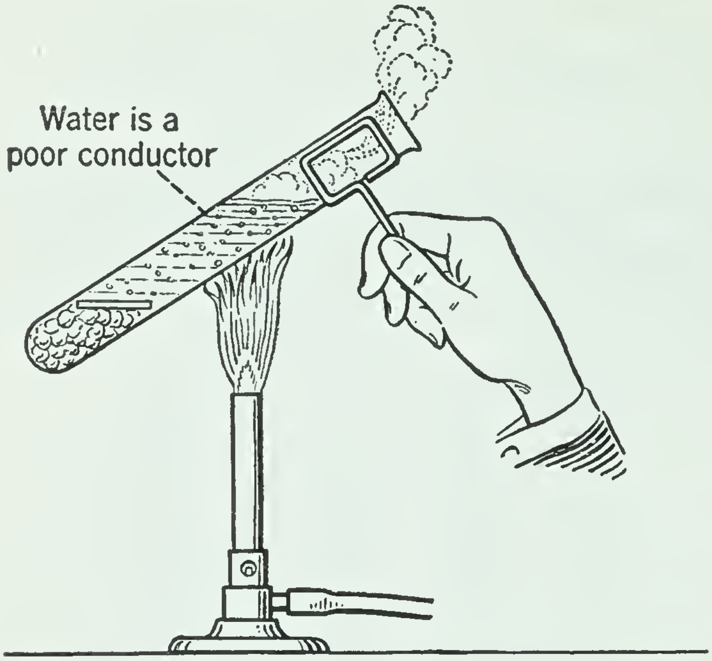

Water is a poor conductor

Fig. 12–2. Water is a poor conductor.

thirds full of water. (See Fig. 12–2.) It is possible to boil the water at the top of the test tube for several minutes before the heat is conducted down the tube through the liquid to melt the ice. Water does conduct heat, but it is a poor conductor.

Demonstration. Try the experiment just described.

A still more sensitive test can be made by the use of the apparatus shown in Figure 12–3. The bulb of an air thermometer is surrounded with water in a large funnel. The stem of the thermometer dips into some colored liquid. Ether is poured on the surface of the water and set on fire. Although the air thermometer is extremely sensitive, yet the liquid column is lowered only a little. This experiment, too, shows that water is a poor conductor. Other liquids, too, are poor conductors.

Gases are very poor conductors. It can be shown by experiment that gases are even poorer conductors of heat than liquids. Silver conducts heat more than 800 times as rapidly as water does, and almost 20,000 times as fast as air. Nonconducting layers of air in porous solids are largely responsible for their poor conductivity. A

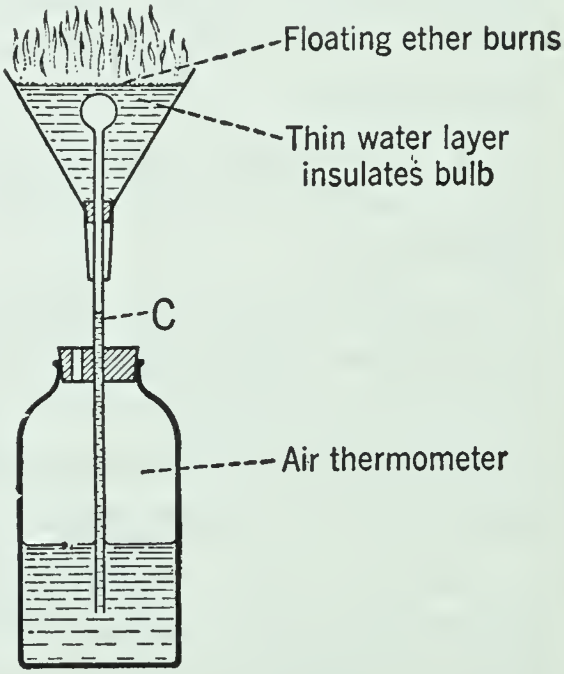


Fig. 12–3. An air thermometer is used to show that water is a poor conductor.

vacuum is a nonconductor of heat, or what is called a heat insulator.

How does conductivity affect our temperature sense? If you walk into the bathroom on a cold morning, you find that the tiled floor feels much colder than a rug which covers a part of the floor. A thermometer would show that both have the same temperature. The tiling feels colder than the rug because it is a better conductor of heat, and it *takes heat from* the foot faster than the rug does. A person who takes a pan of hot bread from an oven gets a more severe burn if he accidentally touches the metal pan than he does by touching the bread in the pan. Both have the same temperature, but the metal is a better conductor, and it transmits heat to the hand more rapidly. If both the pan and the bread were ice cold, then the pan would feel colder to the touch than the bread.

How does clothing keep us warm? The clothing which we wear does not afford us any warmth in winter, but it does prevent the heat of the body from escaping. That kind of clothing which is made of the poorest conducting material seems warmest. Wool and silk seem warmer than cotton and linen because they are poorer conductors. They help the body to retain its heat. Furs are very warm because they contain layers of nonconducting air. Two light garments are warmer than a single heavy one because there is a layer of air between them, and the air acts as an insulator. For the same reason, two light blankets are warmer than one heavy one.

Demonstration. Examine a section of a heavy sweater, using a magnifying glass. Note the air spaces between the strands of wool.

How do we utilize conduction? One portion of a stick of wood or lump of coal is heated until it is kindled. As it burns, the heat is conducted to other portions of the fuel, and they in turn begin to burn. Without conduction, fires would not spread along the various portions of a fuel so readily. Aluminum pans are much used for cooking utensils. The pan conducts the heat to the food which is to be cooked. The outer surfaces of the cylinders of rotary airplane engines and motorcycle engines are covered with deeply corrugated metal, sometimes copper. (See Fig. 12–17.) These projecting blades or fins help to carry away the engine heat and speed up air cooling. The surface layers of the soil absorb the sun's heat, and some of this heat is conducted to the layers beneath.

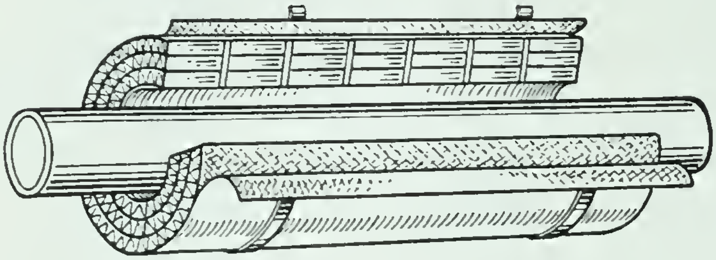


Fig. 12–4. Pipes are covered with heat insulators.

How can insulators be used to save heat? Much money could be saved if more attention were given to insulation in the building of houses. The furnace itself may be covered with "85% magnesia," a substance that is extremely porous, or it may be covered with layers of corrugated asbestos, to keep the heat from escaping to the basement. The steampipes, too, in the basement and in the walls of the house may be covered with heat insulating material to prevent loss of heat before it reaches the rooms where it is wanted. (See Fig. 12–4.) Hot-water storage tanks have their walls insulated with rock wool. Houses are built with double walls and, in very cold climates, with double windows. The air spaces in the walls keep the heat from escaping in winter, and they keep the outside heat from coming in during the summer.

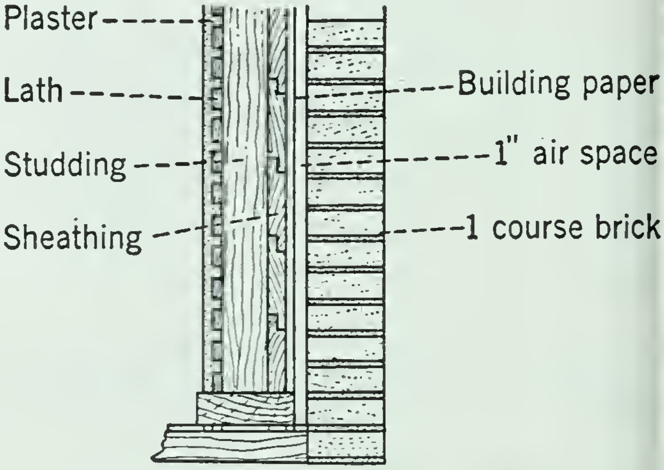
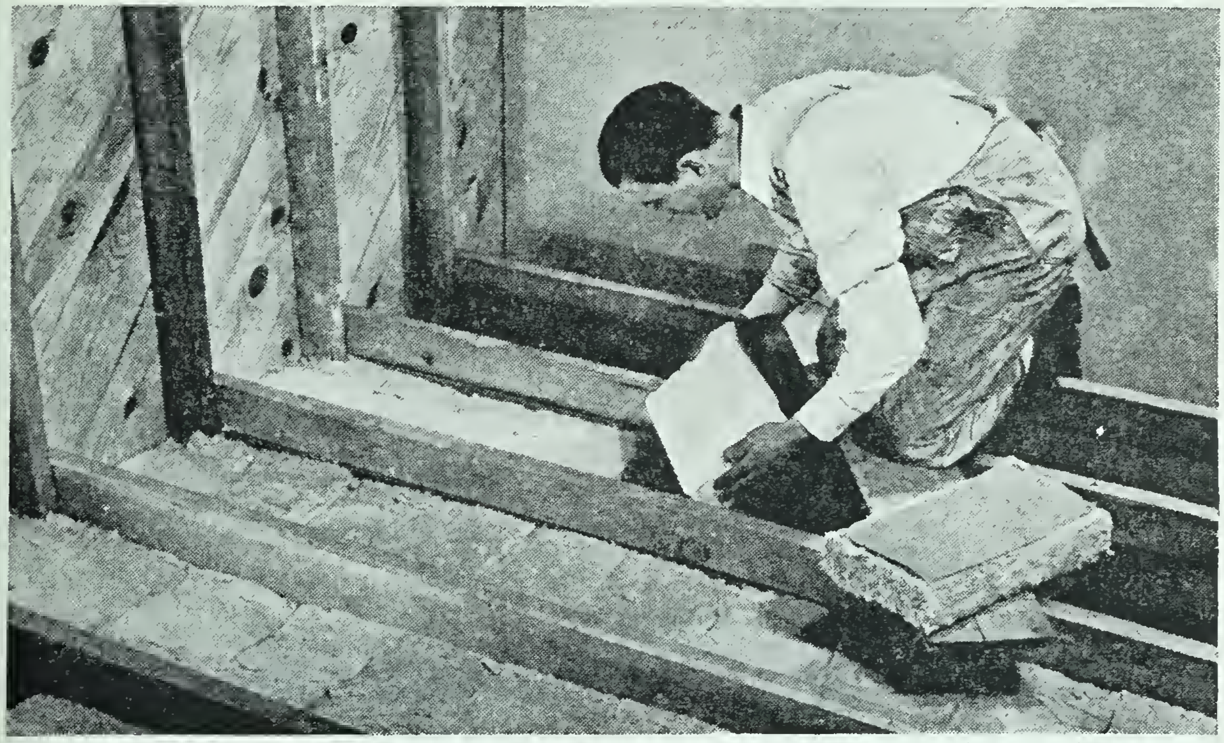


Fig. 12–5. Brick-veneer walls and insulation.

Brick-veneer houses are warm in winter and cool in summer if they are properly constructed. Let us refer to Figure 12–5. The brick course must be kept about one inch from the sheathing to leave an insulating air space. A good building paper, or sometimes a kind of paper quilt is used to cover the sheathing. The space between the sheathing and the plaster is



Courtesy of Johns-Manville Corporation

FIG. 12–6. Rock wool is used to insulate walls and roofs of houses.

filled with rock wool or a light flaky mica called "zonolith," to help insulate the walls. (See Fig. 12–6.) The same material is used between the rafters. Thin sheets of aluminum foil under the name "Alfol" are also used to insulate roofs and walls of houses.

DEMONSTRATION. Exhibit and examine many different kinds of insulation materials such as magnesia, asbestos, rock wool, spun glass, glass brick, etc.

How do modern gas ranges save heat? Many so-called "fireless" gas and electric ranges are now constructed with the idea of conserving heat. The oven in such a range is made with double walls, and the space between the walls is filled with mineral wool or some other heat insulator. When a roast is put in such an oven, the gas is lighted and kept burning for 30 or 40 minutes. Then it is turned off and the oven sealed. The heat absorbed by the walls of the oven is sufficient to finish the cooking of the roast.

A kind of well is used for cooking vegetables by boiling. The walls of this well are heated while the gas flame is being used to bring the water up to boiling, or for the first 10 minutes of the cooking. The walls absorb enough heat to complete the cooking of the vegetables after the gas is turned off.

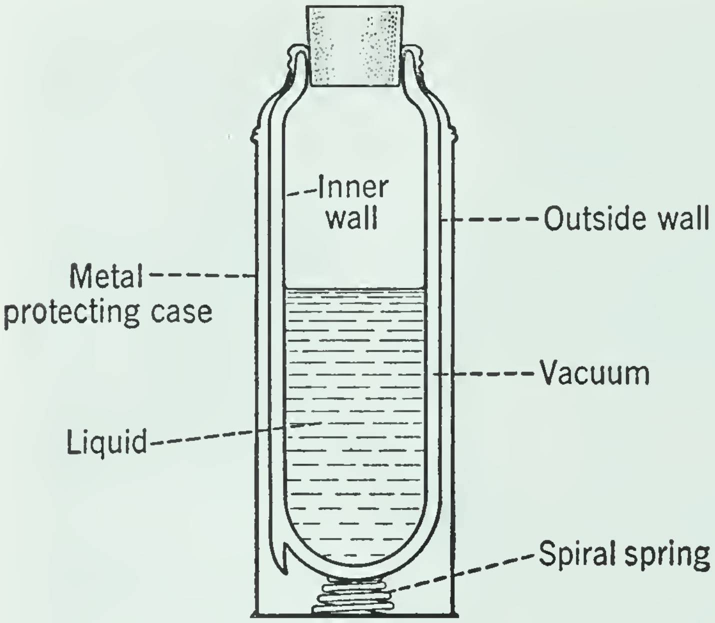


FIG. 12–7. The thermos bottle depends upon the insulating qualities of a vacuum.

The thermos bottle conserves heat. Hot liquids poured into a thermos bottle stay hot a long time, and cold liquids stay cold. This bottle utilizes the fact that a vacuum is a nonconductor of heat. Such bottles are generally made of glass so blown that the walls will be double. (See Fig. 12–7.) The air is then exhausted from the space between the walls, and the bottle is sealed so that no air can then get in. Heat does not pass through the walls by conduction, and the walls are silvered to prevent the transmission of radiant heat.

Some large thermos bottles are mounted on motor trucks. Dairymen chill milk by letting it flow in thin layers over coils containing cold brine and then pour it into huge thermos bottles to keep it cold during shipment.

The refrigerator is a heat insulator. The old saying, "What will keep out cold will keep out heat," is a true one. Our

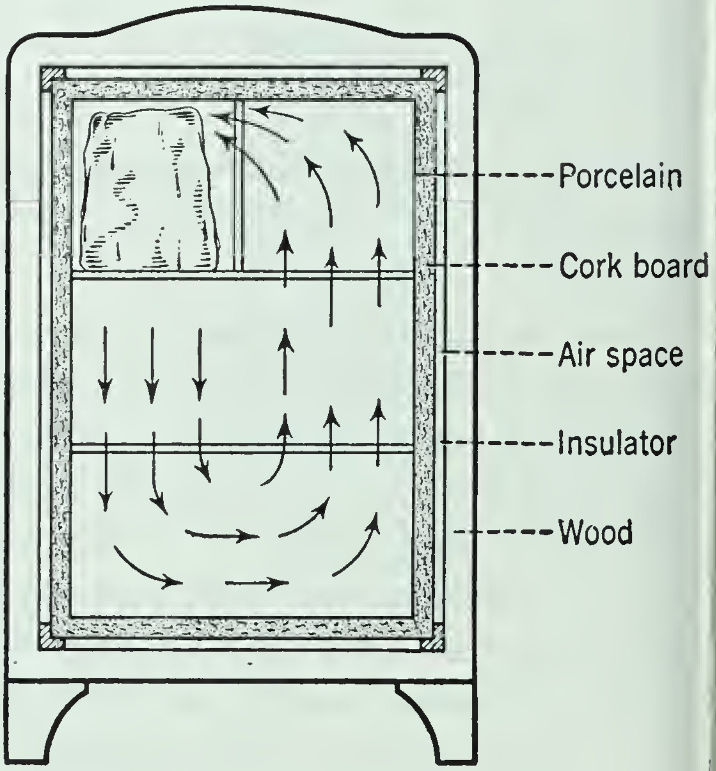
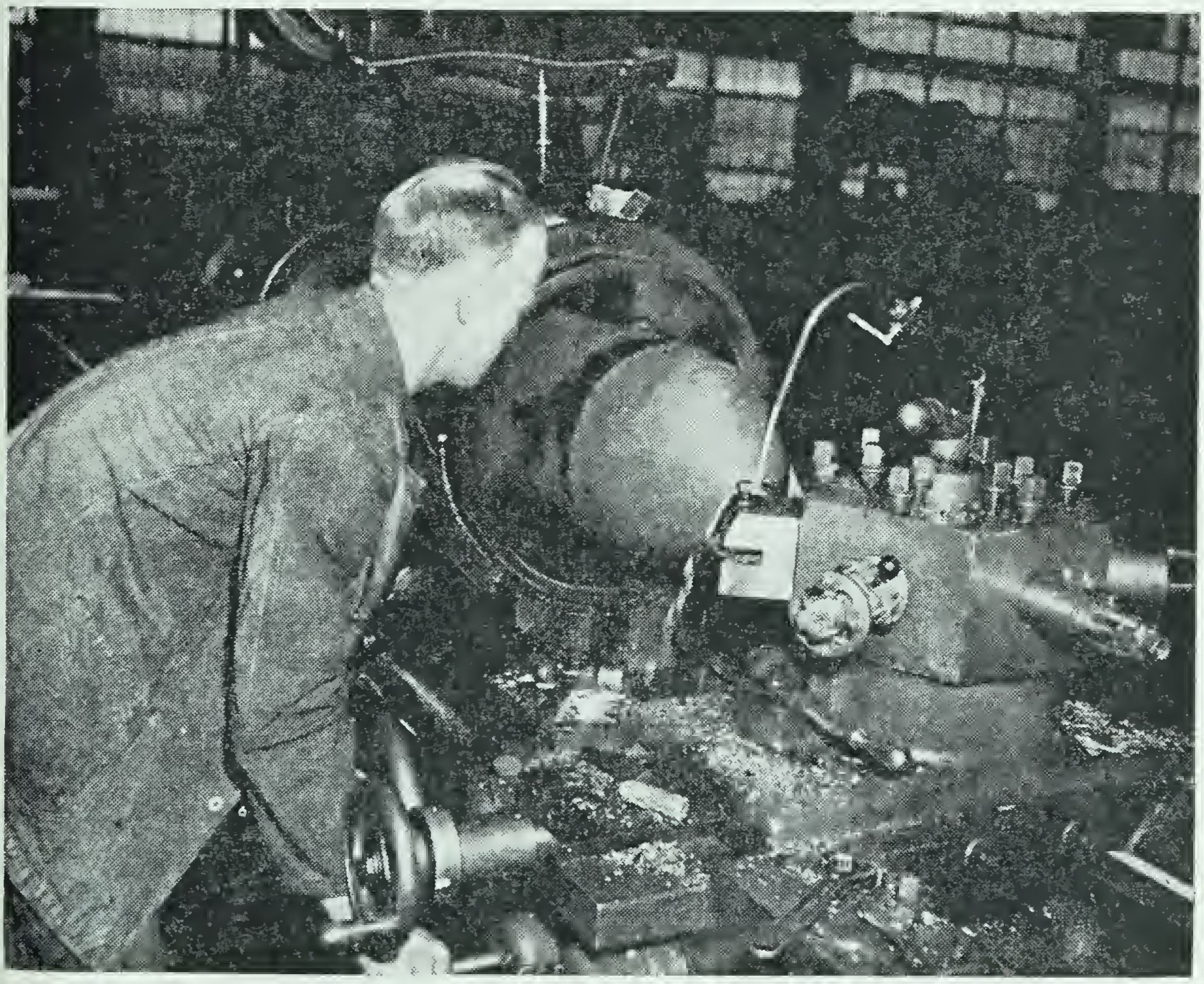


FIG. 12–8. A refrigerator is as good as the insulating material in its walls.

refrigerators are built with this idea in mind. A good refrigerator box has double or triple walls. The space between the walls is filled with such insulating material as corkboard or mineral wool. The door must close tightly and be kept closed as much as possible. The melting ice chills the food. (See Fig. 12–8.)

3. APPLICATIONS OF CONDUCTION TO HEAT ENGINES

How is heat transferred in steam and gasoline engines? In the boiler of a steam engine all the heat absorbed from the flame in the firebox passes through the walls of the boiler and water tubes by conduction. (See Fig. 11–15.) The water tubes increase the con-



Courtesy U. S. Army Signal Corps

Fig. 12–9. The nose of a 500 lb. demolition bomb being machined for the fuse. Notice the cutting oil being poured from the tube to carry away heat of friction and to lubricate the cutting blade.

ducting surface exposed to the fire thus enabling a more rapid rate of heat transfer to the water inside the boiler.

In the gasoline engine the problem is to get rid of heat rather than absorb it. In such engines the heat of the combustion which takes place inside the cylinders results in high temperatures. About 35 per cent of the heat of combustion passes into and through the cylinder wall by conduction. The temperature resulting from the combustion of fuel within the cylinder is approximately 2700° F. Therefore, the amount of heat gained by the cylinder wall is great. This fact necessitates the use of some effective cooling system.

For water-cooled cylinder walls it has been found that temperatures around 160° to 190° F. are the most satisfactory. For air-cooled motors a good working temperature is around 300° F. Should the cylinder walls become too hot, the lubricating oil would be burned, thus allowing friction between the walls and the pistons quickly to damage the wearing surfaces.

Many special machines, such as lathes and drills, use streams of oil to carry away heat of friction by conduction. (See Fig. 12–9.)

B. CONVECTION

1. CONVECTION CURRENTS IN LIQUIDS AND GASES

What is the principle of convection? Suppose that we add a few particles of sawdust to a beaker nearly full of water and heat it near one edge as shown in Figure 12–10. The water directly over the flame expands and becomes less dense. The heavier water from the opposite side of the beaker sinks, flows across, and pushes up the lighter water, thus setting up *convection currents* as shown by the arrows. The circulatory movement of the water is shown by the motion of the sawdust particles.

If we light a heater in the center of a large room, the air over the heater will expand. This lighter air is pushed upward by the colder, heavier air flowing in along the floor toward the center of the room. As the warm air reaches the ceiling, it spreads out toward the walls, sinking downward again as it cools. *Convection currents* may be set up in either liquids or gases by unequal heating. By means of such currents, heat is *transmitted by the movement of the heated masses.*

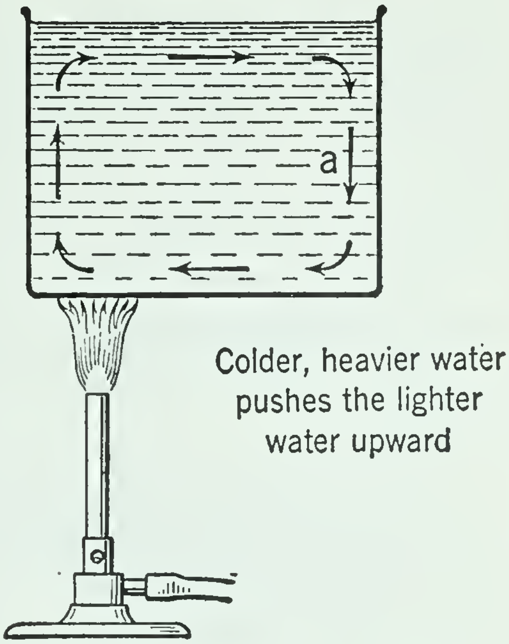


Fig. 12–10. Convection currents in liquids.

How shall we ventilate? The whole plan of ordinary ventilation depends upon convection. The air which we exhale is warmer and lighter than out-of-door air. The foul air may be pushed out of an open window near the top of a room by the fresh air which enters nearer the floor. The three diagrams of Figure 12–11 show clearly how convection currents are useful in ventilating rooms. For ventilating large buildings and mines, compressed air is in common use.

What is air conditioning? The average adult eats about a ton of food every year, but during the same time he breathes more than six tons of air. We wrap our foods in cellophane, and we hire inspectors to test the purity of our foods, but relatively little attention is given to the proper conditioning of air.

The engineer has found that at least four things need to be done in the proper conditioning of air if one is to be comfortable, efficient, and healthy.

(1) The air must be warmed in winter and cooled in summer. Man can adapt himself to ex-

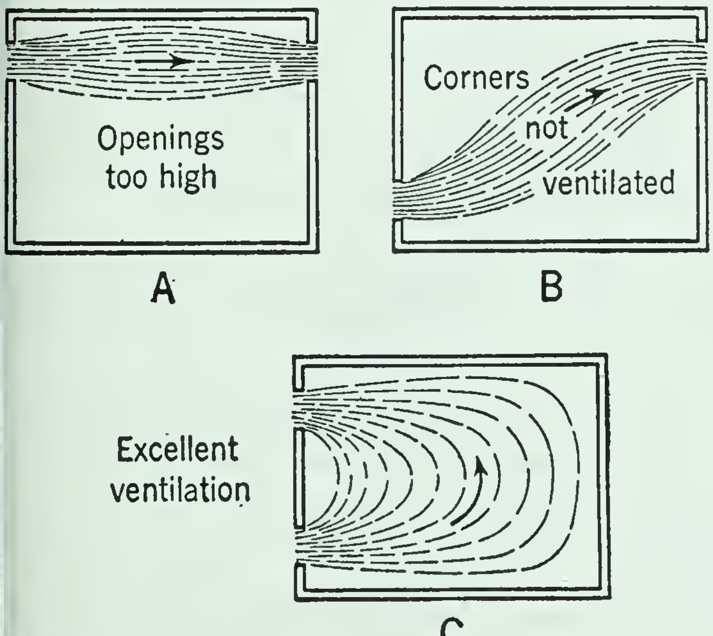


Fig. 12–11. A room should have cross-ventilation, without direct draft.

tremes of temperature, but he works most efficiently when the temperature range is from 63° F. to 75° F.

(2) The relative humidity should not be less than 30%, nor more than 70%, preferably between 40% and 60%. One often hears the expression, "It isn't the heat; it's the humidity."

(3) Air should be filtered to remove particles of dust and bacteria that are always present in air to some degree. The accumulation of dust particles in the lungs is responsible for diseases of these organs.

(4) The air must be kept in constant, gentle motion.

Air-conditioning units are available for hotels, trains, office buildings, schools, and homes. In such units, the air is filtered. It is warmed in winter and cooled in summer. Moisture is removed from the air when it is present in excess, and the air is moistened when it is too dry. A fan driven by an electric motor keeps the air in motion. The expense of installing and operating air-conditioning units is the only thing that keeps them from becoming very popular.

Why does a chimney draw? We know that a chimney draws when the wind blows across the top because of Bernoulli's principle. But even on a calm day there is an upward draft in a chimney if there is a fire in the furnace or stove. Before the fire is started, the air inside the chimney has the same density as the air outside. But when the fire is started, the air above it expands. Colder, heavier air from outside then pushes the warm air up the chimney and also the hot waste products formed by combustion.

A tall chimney draws better than a short one, because there is a greater difference in weight between the hot gases inside the chimney and an equal volume of cold air outside.

What causes winds? The unequal heating of the air at different places on the earth's surface causes huge convection currents in the atmosphere. In this way winds are caused. Let us study some of them in greater detail:

(1) *Land and sea breezes.* For several reasons, water in the oceans heats more slowly than the land along the shore. It has a higher specific heat than the land; it is transparent, allowing the sun's

heat rays to penetrate to greater depth; and it is in more or less constant motion. Hence, by the middle of the forenoon on a sunny day, the land area, and also the air above such an area, will be more highly heated. The colder, heavier air from the ocean blows in and forces the lighter air upward. Along the coast, a *sea breeze* comes up in the middle of the forenoon and blows steadily until late evening. (See Fig. 12–12.)

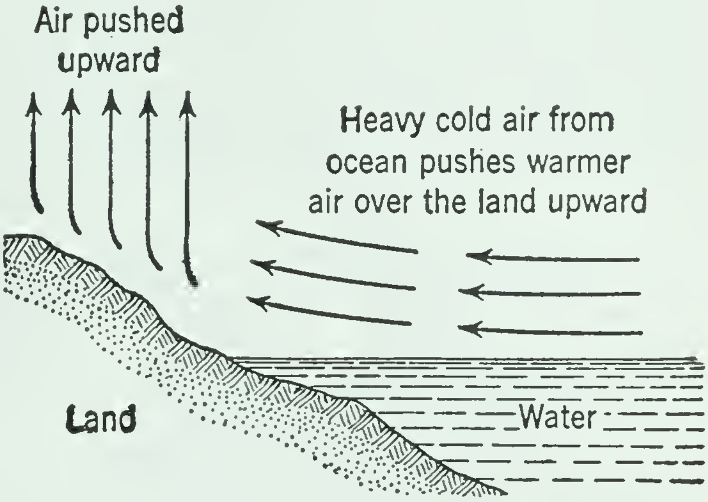

Air pushed upward
Heavy cold air from ocean pushes warmer air over the land upward
Land
Water

Fig. 12–12. Sea breezes blow toward the land during the day.

At night, the land cools more quickly than the water, and the air over the ocean becomes warmer than it is over the land. A *land breeze* then blows toward the ocean, usually beginning shortly before midnight. Fishermen along the coast use the land breeze to go to sea at night; they return in the forenoon with the sea breeze. (See Fig. 12–13.)

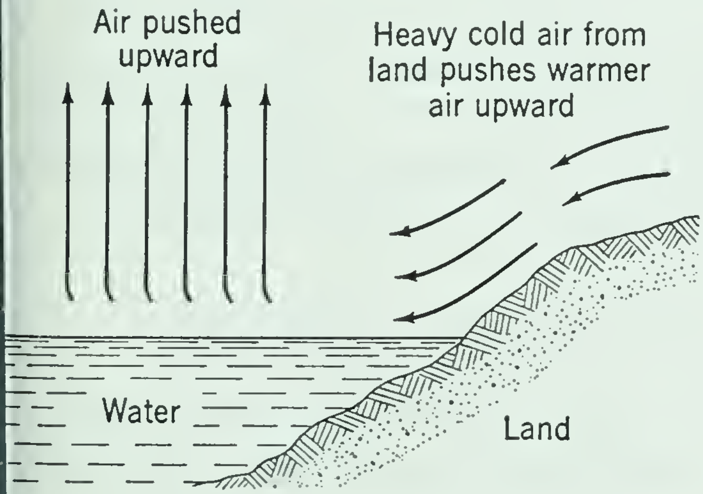


Fig. 12–13. Land breezes

(2) *Monsoons.* These winds are like land and sea breezes, but they are *seasonal.* In some localities, the land areas are so intensely heated in *summer* that the wind blows continually toward the land for a period of about five months. After about one month of more or less variable winds, a huge land breeze blows toward the warmer ocean during the *winter* season.

(3) *The trade winds.* The vertical rays of the sun in the vicinity of the equator, in March or September for example, heat the equatorial areas strongly and produce upward air currents. Where

the air is being pushed upward, there is no lateral movement of air, but a calm belt known as the *equatorial calm belt,* or the doldrums. Colder, heavier air blows toward the equator from both the north and the south. These *trade winds* blow continually throughout the year. We would expect the trade wind south of the equator to blow due north and the one north of the equator to blow due south, but the rotation of the earth on its axis deflects them. In the southern hemisphere we have the *southeast trades,* and in the northern hemisphere the *northeast trades.* (See Fig. 12–14.) The warm air over the equator is being pushed upward by the colder air of the trades drifting toward the equator. There are abnormally high pressure areas over the Tropics of Cancer and Capricorn. The air currents there are descending. For that reason we have the *Calms of Cancer and Capricorn* known to sailors as the "horse latitudes." Figure 12–14 shows the general atmospheric circulation in the spring and fall. During our summer, the calm belts and the trade winds shift northward. In the winter they shift southward.

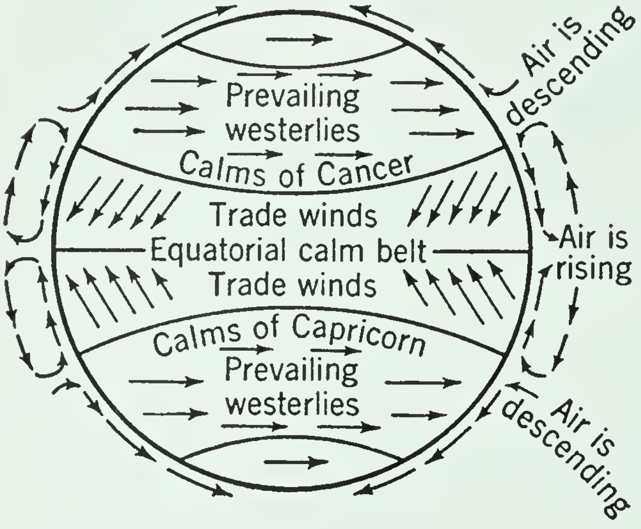


Fig. 12–14. This chart shows atmospheric circulation when direct rays of the sun shine on the equator.

2. APPLICATIONS TO HEAT ENGINES

Convection currents help to supply air to burn the fuel in the firebox of a steam engine. Water is circulated from the boiler through the water tubes in the firebox by convection currents. A great deal of the heat reaches the water tubes and bottom of the boiler from the flame by convection.

In the internal-combustion engine the water-cooling system is most commonly used. In this system there are two general methods of circulating the water through the jackets surrounding the cylinders. One depends upon convection currents set up by the warm water rising and the cool water sinking. This is known as the thermosyphon method. The second method most commonly used for circulating the water is the forced or pump method. (See Fig. 14–8.) In both methods as the water circulates around the cylinder walls it gains heat by conduction and carries it, either by convection currents or by pump, to the radiator.

DEMONSTRATION. Soak some finely divided sawdust in a large beaker of water. Heat the beaker over a Bunsen flame. Note the circulation of the particles of sawdust. Explain.

Shake chalk from an eraser over and to the side of a radiator. Repeat over a Bunsen burner flame. Note the air currents. Explain.

C. RADIATION

1. WAVE FORM OF RADIATION

Ether transmits radiant energy. When the hand is held in front of a fireplace, it is quickly warmed by radiation. In the same manner we receive heat from the sun. Since heat is a form of energy produced by the motion of the molecules, waves are set up in the surrounding medium. Huygens advanced the wave theory to account for the transmission of radiant energy. Radiations travel through a vacuum; so he presupposed the existence of a very subtle medium which pervades all space and transmits radiant energy. This medium is called *ether*. It is supposed to be an invisible fluid, so very rare that it cannot be weighed or measured; it easily penetrates intermolecular spaces. *The absorption of radiant energy produces heat in the absorbing medium. Substances easily penetrated by the ether waves are little warmed by their passage.*

2. COLOR AND POLISH DETERMINE ABILITY TO REFLECT, ABSORB, AND RADIATE HEAT

Some surfaces are better radiators than others. When heat waves are incident upon an object, a part are reflected, part may be transmitted, and the rest are absorbed. Polished metals are the best reflectors known; hence they are very poor absorbers of heat. A poor absorber of heat is also a poor radiator. A roughened teakettle absorbs heat more readily than a highly polished one; it also loses heat faster by radiation.

The color of a substance also affects its absorbing power. A black surface absorbs heat faster than a white one. Hence, light-colored garments are cooler in summer sunshine than black ones. Lampblack is the best absorber known and also the best radiator.

Crookes' radiometer may be used to demonstrate these facts. It consists of a partially exhausted bulb, in which is suspended a light aluminum wheel that has a set of vanes in its circumference. Each vane is polished on one side and covered with lampblack on the other. When exposed to a source of radiant energy, heat is absorbed more rapidly by the black surfaces. The adjacent air is more highly heated and the molecules rebound with a greater velocity from the black surfaces, thus exerting greater pressure and causing the wheel to rotate in the direction shown in Figure 12–15.

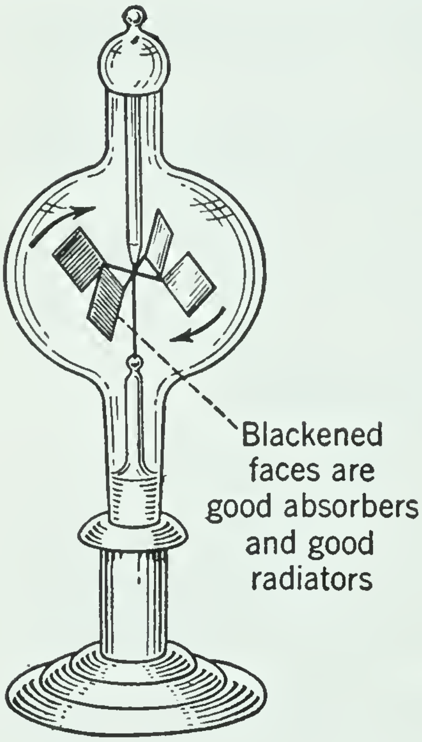


Fig. 12–15. A Crookes' radiometer operates in sunlight.

By the use of Leslie's cube and a *differential* thermometer, it may also be shown that a black surface radiates heat faster than a white one. (See Fig. 12–16.) Surfaces of the cube are painted different colors. It is filled with hot water and supported so that the black face will be the same distance from bulb A of the thermometer that the white face is from bulb B. Since bulb A is heated more rapidly by radiation from the black surface, the air within this bulb expands more and forces the liquid C down the tube.

What are the laws of radiation? When the moon comes between the sun and the earth during an eclipse of the sun, it cuts off both the heat rays and the light rays at the same time. Since light is known to travel at a velocity of more than 186,000 miles per second, we conclude that heat waves travel at the same velocity. Heat waves also travel in straight lines.

If you are sitting near a fireplace you receive more heat than someone who is farther away. The higher the temperature of a radiator, the more heat waves it gives off by radiation. Measurements show that the *intensity of radiant energy is directly proportional to the temperature of the source, and inversely proportional to the square of the distance.* The planet Mercury is only about one-third as far from the sun as the earth; hence it must receive about nine times as much radiant heat as the earth receives.

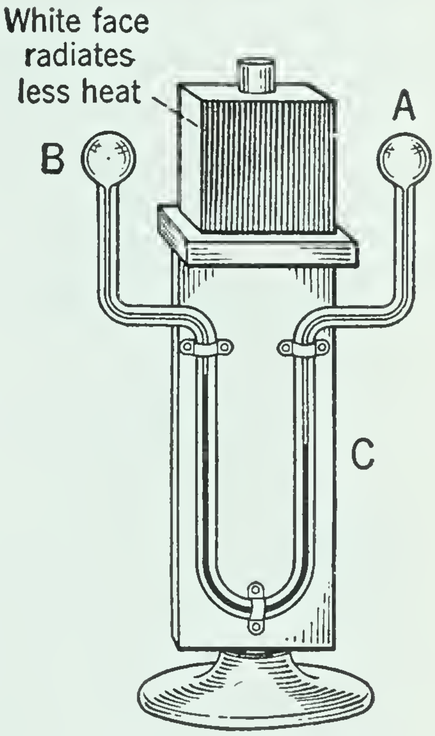


Fig. 12–16. Leslie's cube and a differential thermometer.

Suppose we put two cups of warm water in a refrigerator to cool. The refrigerator has a temperature of 50° F.; one cup of water has a temperature of 60° F., and the temperature of the other is 70° F. By the use of a thermometer it may be shown that the latter cools twice as fast as the former. It is 20° warmer than the refrigerator and the former is only 10° warmer. NEWTON'S LAW OF COOLING may be stated as follows: *The rate of cooling by radiation is proportional to the difference between the temperature of the cooling body and the surrounding medium.* A house at 60° F. cools off twice as fast when the outside air is 20° F. as it does when the temperature is 40° F.

What is heat transparency? When the ether waves produced by radiant energy pass through a substance without heating it, then the substance is said to be *diathermanous.* Substances opaque to heat are *athermanous.* Dry air is quite transparent to heat, but air containing much water vapor is much more opaque. Clouds absorb heat as it travels from the sun to the earth, and they prevent, to a great extent, the loss of heat from the earth by radiation. On high mountains the sun's heat is intense.

Some substances are transparent to light, but opaque to heat. Alum is an example. Conversely, iodine solution is opaque to light, but transparent to heat.

Heat from the sun readily comes in through glass windows, but heat from the radiators does not pass out through glass readily. If the temperature of the source of heat is very high, its waves are short and very penetrating. The heat waves given off from a radiator are long waves and much less penetrating. Glass is used for covering greenhouses and "cold frames"; the heat from the sun passes in through the glass, but there is little loss by radiation.

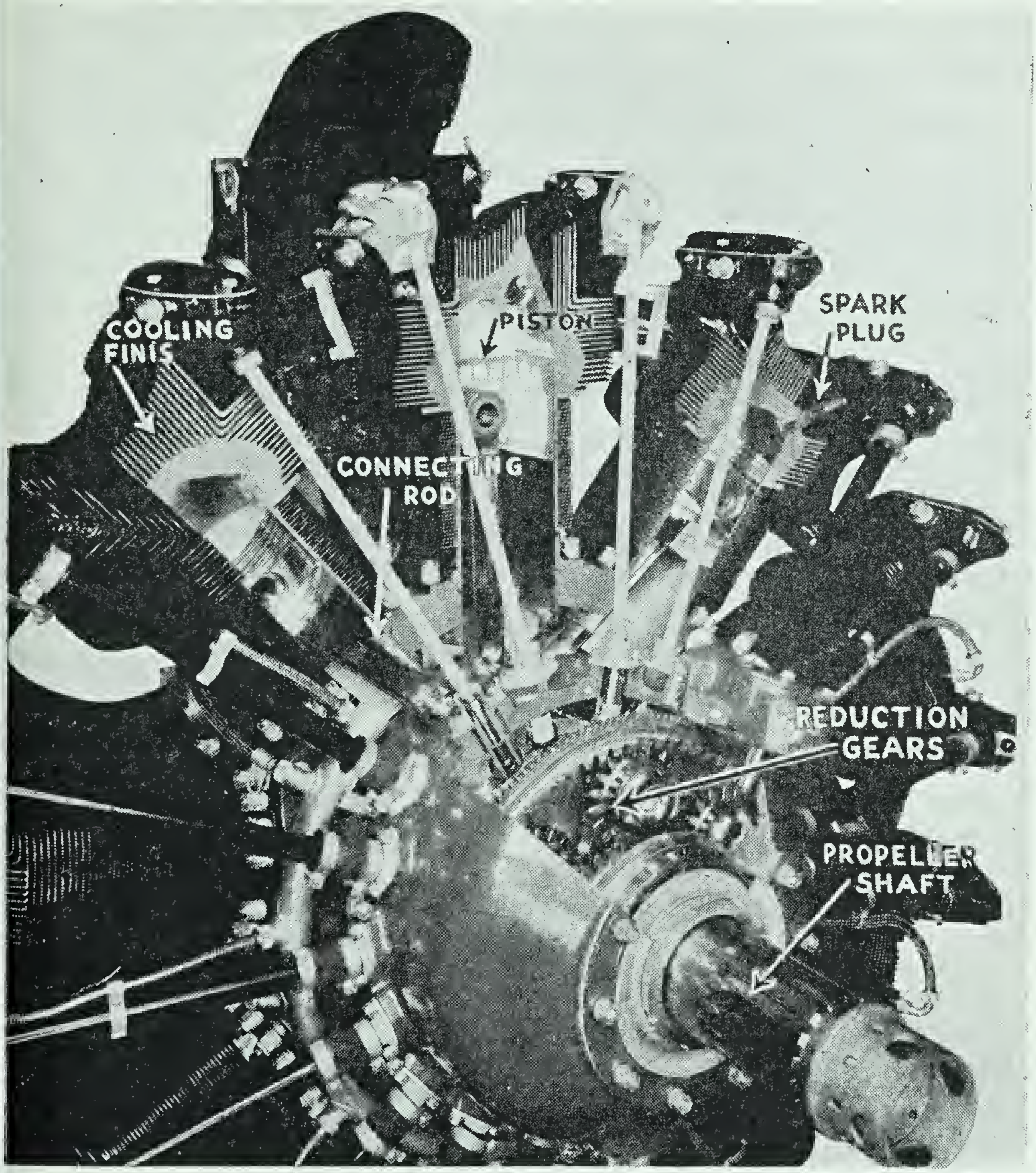
3. APPLICATION TO HEAT ENGINES

Methods of cooling motors. The motor loses its heat by conduction to the tubes of the radiator, which in turn lose heat by radiation to surrounding space and by conduction to air currents set up by the fan.

Air cooling is another general method of cooling engines which is being successfully used in small motorboat, motorcycle, and aircraft engines. The principal advantages of this method are as follows: the air-cooling system is not subject to freezing, the weight of the motor per horsepower is less than that of water-cooled motors, and it utilizes a larger percentage of the fuel energy for the production of power. Such motors have fins or ribs cast on the outside of the cylinders to increase radiation surface as well as to increase surface exposed to air currents. (See Fig. 12–17.)

Much of the heat of the fire in a firebox of a steam engine is transmitted to the boiler by radiation.

Demonstrations. (1) Expose a radiometer to a Bunsen flame (at a distance of a few feet), to an electric light, and to sunlight. Heat an iron ball supported in a ring on a ring stand. Hold the radiometer two or three feet from the ball. Note the behavior of the radiometer in each case and give an explanation.



Courtesy of the Wright Aeronautical Corporation

Fig. 12–17. Wright Cyclone engine.

(2) Support two air thermometers, one with the bulb painted white nd the other with the bulb coated with lampblack. Place colored water n each to an equal height. Give the two bulbs equal exposure to either Bunsen flame or an electric light. Note the change in water level in each hermometer. Which bulb absorbed light energy faster? Explain.

SUMMARY

1. Heat may be transmitted by conduction, convection, and radiation. Solids conduct heat better than liquids or gases. Convection does not occur in solids.

2. Good conductors feel hotter than they really are, if their temperature is higher than that of the hand; when their temperature is lower than that of the hand, they feel colder.

3. Heat insulation is extensively used in house construction, building refrigerators, covering pipes, and in fireless ranges.

4. Convection depends upon the fact that fluids expand when heated. Ventilation systems, hot-air and hot-water heating systems, and atmospheric circulation all depend upon convection currents.

5. Good absorbers of heat are good radiators. Good reflectors are poor absorbers and poor radiators.

6. Both steam engines and internal combustion engines utilize all three methods of heat transmission in changing heat energy into mechanical energy.

How many of the following terms can you define or explain?

Conduction
Insulator
Convection
Air conditioning
Land breeze
Sea breeze
Radiation
Ether
Transparency
Opaqueness
Diathermanous
Athermanous

SELF-TESTING EXERCISES

Complete These Statements

On a separate sheet of paper numbered from 1 to 10 write the words needed to fill correctly the blank spaces in the following sentences.

Heat is transmitted from one end of a metal rod to another by ..(1)... The usefulness of a fireless cooker depends upon its ability to ..(2).. heat. Houses are built with hollow walls because air is a ..(3)... A tiled floor feels colder than a rug in the same room because the tile is a ..(4)... Gases are very ..(5).. conductors. Porous solids are good

..(6)... Liquids and gases may transmit heat by means of ..(7)... Sea breezes are due to the fact that water cools ..(8).. than land. In the hot-water heating system the most important method of distributing heat is ..(9)... Poor radiators of heat are ..(10).. absorbers.

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 10 write a T *or an* F *to show whether each statement is true or false.*

1. Heat from the sun reaches the earth by conduction.
2. Rough black surfaces are good radiators.
3. Woolen clothing is warmer than linen, because it is a better heat insulator.
4. Tea will cool more quickly in a highly polished metal pot than in a tarnished one.
5. In the equatorial calm belt, warm air descends in the daytime.
6. The purpose of fins on the outside of the cylinders of air-cooled engines is to increase the contact with air in order to lose heat more readily.
7. A substance which allows ether waves to pass through it is said to be transparent.
8. A substance which will not allow ether waves to pass through it is a diathermanous substance.
9. Short ether waves are produced by very hot objects.
10. Short ether waves are more penetrating than long ether waves.

QUESTIONS

1. Why does wrapping ice in a woolen blanket keep it from melting rapidly? Is ice of much value in a refrigerator unless it melts? Explain.
2. Why does a chimney "draw"? How does the height of the chimney affect the draft? Why does a chimney "draw" better on a clear, cold day than in damp, cloudy weather? Explain why a chimney "smokes" when a new fire is started.
3. Why are houses built with hollow walls?
4. Why do stove lifters and pokers usually have wooden or coiled wire handles?
5. Why do workmen around furnaces wear woolen clothing even in summer?
6. Does clothing supply us any heat in winter? How does it keep the body warm?
7. How does snow protect the grass in winter?

8. In making ice cream, why is the cream usually put in a metal container and the ice in a wooden container?

9. Is it economy to keep stoves highly polished? Explain.

10. Why does dew or frost seldom form on cloudy nights?

11. On high mountains the sun is exceedingly hot in the daytime, but the temperature usually falls below freezing at night. Explain.

12. Why does it rain nearly every afternoon in the equatorial regions?

13. Why is it necessary for a radiator to have more sections when used with hot water than with steam heat?

14. Does tea cool more quickly in a tarnished metal pot or in a highly polished one?

15. Which is warmer, cotton or linen clothing? Why?

16. Why does mist often form in the receiver of an air pump?

17. Since solids are better conductors of heat than gases, why does packing rock wool in the walls of houses or between the rafters help to insulate a house?

18. Why is silvered glass used in making thermos bottles?

19. Two pieces of cloth are laid upon the snow. One of them is black; the other, white. The black one sinks into the snow faster on a sunshiny day. Why? If we cover the black one with powdered alum and the white one with powdered iodine, the condition will be reversed. Explain.

20. In what way do double windows save fuel?

21. Why are steampipes in the basement covered with asbestos or magnesia?

22. Why does the tongue or a moistened finger freeze to a cold metal, but not to wood of the same temperature?

23. Is it economical to have steam radiators highly polished? Would it be economical to have them painted black?

24. How does heat get from the radiators to the various parts of a room?

25. Make a list of at least six heat insulators used in a dwelling house.

26. At the tropics, air currents are descending. Account for the arid regions there.

27. Why is the air-cooled motor not commonly used by automobiles?

28. What advantages has an air-cooled motor?

XIII

Fuels Furnish Energy for Machines

A. THE CHEMISTRY OF COMBUSTION

1. NATURE OF MATTER

Matter is made up of elements, compounds, and mixtures. As you have already seen (Chapter I), matter is anything which occupies space, and has weight. The chemist has found that all matter exists in the form of *elements*, *compounds*, and *mixtures*. Because all efforts by chemical means to decompose certain substances, such as carbon, sulfur, iron, copper, and gold, into simpler substances have failed, the chemist considers them elements. The smallest particles of elements are called atoms. Other substances, such as water, salt, and sugar, can be decomposed into elements. Repeated tests have shown that each of these substances is always composed of the same elements and in exactly the same proportion by weight; such substances are therefore called compounds. The molecule is the smallest particle of a compound. Mixtures may be composed of elements or compounds, or elements and compounds, but these are not chemically combined. A mixture, therefore, has no definite composition.

Can an element be broken up into simpler substances? You may analyze a complex or a compound sentence into subject, predicate, object, or modifiers. We may consider them the elements of which the sentence was composed. In a similar manner, a chemist may start with a complex mixture of substances, or with a compound, and separate or decompose it into simpler substances by analysis. Let us use water as an example.

By passing an electric current through some water to which a little acid has been added, it is possible to show that water can be decomposed into two gases, hydrogen and oxygen. Hence water must be composed of hydrogen and oxygen. (See Fig. 13–1.) We call them *elements, because all attempts to split either hydrogen or oxygen into anything simpler by chemical means have resulted in failure.* The products that are formed by analyzing a substance as completely as we can are called elements.

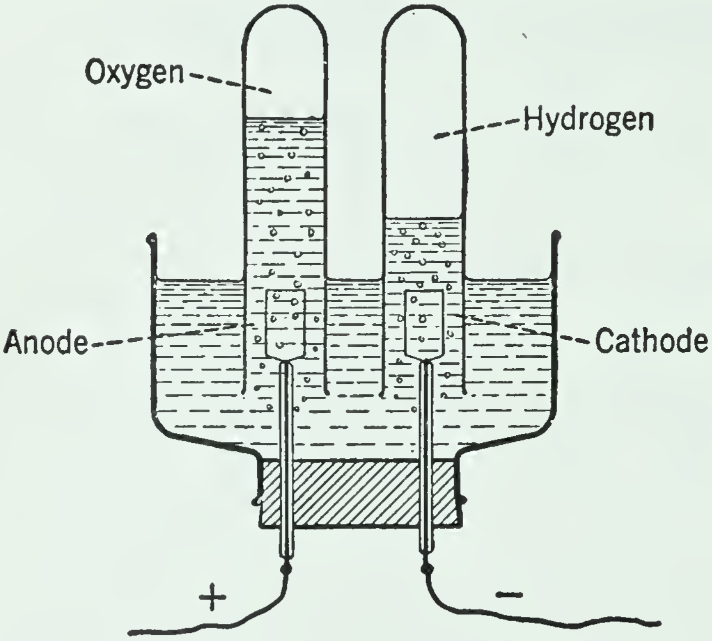


FIG. 13–1. An apparatus of this type may be used to decompose water by electrolysis.

How have men's ideas of elements changed? Aristotle, one of the early Greek philosophers, considered air, fire, earth, and water as elements. Now we know that air is a mixture of gases, water is a compound, fire is the result of heat energy, and earth is a mixture of several different substances. Until 1766, water was considered an element. At that time Henry Cavendish recognized hydrogen as an element and found by experiment that it combines with oxygen to form water. Since a chemist can make oxygen and hydrogen unite to form water, or can decompose water into hydrogen and oxygen, we are now certain that *water is a compound.*

It is quite impossible to prove that any given substance is an element. We know that no one has yet succeeded by chemical means in decomposing iron, copper, oxygen, or gold into anything simpler, but we cannot prove that someone may not succeed in doing so in the future by some method as yet untried. The *atom* is considered the chemist's unit. When mixtures and compounds are analyzed, they are separated into their atoms.

How many elements are there? New elements have been discovered from time to time, and it is possible that new ones may be discovered in the future. At the present time, ninety-two substances are known which chemists have good reason to consider elements. (The discovery of alabamine and virginium has not yet been fully confirmed because they exist in such small quantities that it is difficult to get enough to make conclusive tests.) There are good reasons for believing that no more elements will be discovered, and that the earth's crust is composed of only ninety-two elements.

Only about thirty elements are well known, even to fairly well-educated persons. Lanthanum is not a household word, and people might think you were speaking a foreign language if you were to mention such names as dysprosium, praseodymium, gadolinium, or ytterbium.

What are the most abundant elements and where do we find them? Several different elements are present in air, but two elements, nitrogen and oxygen, comprise almost 99% of dry air. Water, a compound of hydrogen and oxygen, is widely distributed over the earth. The rocks and the soils of the earth's crust are composed of compounds and mixtures of many different elements. F. W. Clarke, of the United States Geological Survey, once estimated the relative abundance of eight elements found in air, in water, and in the earth's crust (near the surface only). They make up about 98% by weight of the crust:

Oxygen	49.9%	Calcium	3.4%
Silicon	26.0%	Sodium	2.3%
Aluminum	7.9%	Potassium	2.3%
Iron	4.4%	Magnesium	2.1%

From such figures we see that oxygen comprises nearly half of the earth as we know it, and the element silicon, which is found in sand, clay, and many minerals, comprises more than one-fourth. We must keep in mind the fact that such figures are only an estimate, because nothing is known of the composition of the earth's crust below a depth of a few miles.

Can elements be classified? Elements differ enough in their properties so that chemists recognize two classes: *metals and nonmetals.*

1. *Metals.* Some elements have a luster similar to that of steel or silver. They reflect heat and light readily. They conduct heat

and electricity remarkably well. Some of them may be drawn into wire or hammered into sheets. Elements which have such properties are known as *metals.* Some examples of metals are gold, silver, copper, iron, zinc, tin, lead, magnesium, calcium, and aluminum.

2. *Nonmetals.* Sulfur is a typical example of a nonmetal. It is a poor conductor of heat and electricity. It has a *vitreous* or glassy luster. It cannot be drawn into wire or hammered into sheets. Other nonmetals that are solid at room temperature, which we assume to be 68° F. or 20° C., are carbon, iodine, and phosphorus. Such gaseous elements as oxygen, nitrogen, and chlorine are also nonmetals.

How do mixtures differ from compounds? When matter is made up of two or more elements, they may be mechanically mixed, or they may be united with one another chemically. (See Fig. 13–2.) It is very important for you to understand the difference between a *mixture* and a *compound.* Suppose we perform the following experiment.

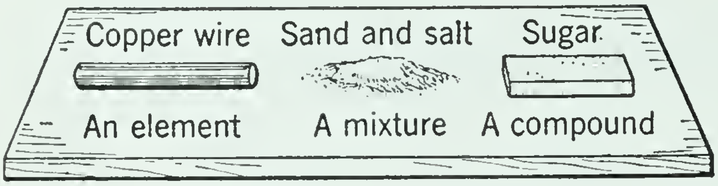


Fig. 13–2. Both mixtures and compounds are made up of elements. In compounds the elements are united chemically.

Demonstration. To some iron filings on a sheet of paper we add some powdered sulfur, and stir the two elements together. No light is produced and no heat is given off. There is no evidence of any action. We find that the two elements may be *mixed* in any proportion, since it is possible to use two parts of iron filings to one part of sulfur, two parts of sulfur to one part of iron filings, or one part of one of them to one hundred parts of the other. We pass a magnet over the mixture and observe that the iron filings cling to the magnet just as they do when sulfur is not present. The iron filings can be dissolved in an acid, but the sulfur does not dissolve. The iron has not lost its characteristic properties. The sulfur retains its yellow color, and does not seem to have lost its special properties. We may consider this behavior as typical of that of a *mixture.* The components do not lose their identity, they may be mixed in any proportion, and there is no evidence of any chemical action when they are being mixed.

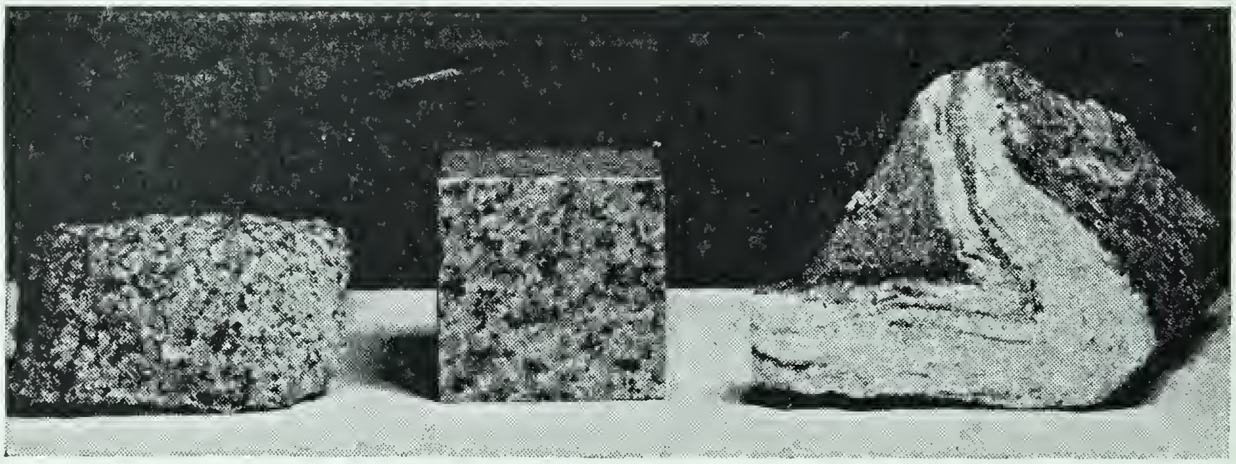
Possibly we can make the iron filings and the sulfur unite chemically to form a *compound.* Let us mix seven parts by weight of fine iron filings with four parts by weight of sulfur and pour enough of the mixture into a test tube to fill it one-third full. Then we heat the mixture until it begins to glow. Even after we remove the tube from the flame, the action continues, and the whole mass will soon become red hot. *Both heat and light were produced during the chemical action which caused the sulfur to unite chemically with the iron to form a compound.* The attraction between atoms which causes them to unite and form compounds is called *chemical affinity.* This experiment is typical of the formation of compounds.

Let us break the tube and examine the product. It does not resemble either the iron or the sulfur. Each element has lost its characteristic properties. The iron cannot be removed by a magnet. The sulfur cannot be picked out of the product mechanically. *A new substance with a new set of properties has been formed.* If we took the product to a chemist to have it analyzed, he would find that the new product is made up of seven parts by weight of iron to four parts by weight of sulfur. *A compound is always made up of the same elements in a definite proportion by weight.* For example, the new compound, which chemists call *iron sulfide,* is always composed of 63.63% of iron and 36.37% of sulfur. That does not mean that we could not make iron sulfide by starting with eight parts of iron and four parts of sulfur, but it does mean that in such a case one part by weight of iron would remain as an unused surplus after the seven parts of iron had combined with four parts of sulfur.

DIFFERENCES BETWEEN A MIXTURE AND A COMPOUND

Mixture	Compound
In a mixture the components may be present in any proportion.	*A compound always has a definite composition by weight.*
In the preparation of a mixture, there is no evidence of any chemical action, such as the evolution of heat, light, or electrical energy. No gas is set free.	*In the preparation of a compound, some evidence of chemical action is usually apparent. Heat, light, or electrical energy may be produced, or a gas may be liberated.*
In a mixture, the components do not lose their identity. The components of a mixture may be separated by mechanical means.	*In a compound, the constituents lose their identity. The constituents of a compound can be separated by chemical means only.*

What are some common examples of mixtures and compounds? Air is a mixture; its composition varies somewhat in different localities. Hash is a mixture; one can identify or even pick out the particles of meat and potato. Its composition varies widely, too. Salads are mixtures, too. Other examples of mixtures include baking powders, granite, concrete, and various kinds of soil. There is practically no limit to the number of mixtures that it is possible to have, because they may be made up of two or more elements, of two or more compounds, or of both elements and compounds. (See Fig. 13–3.)



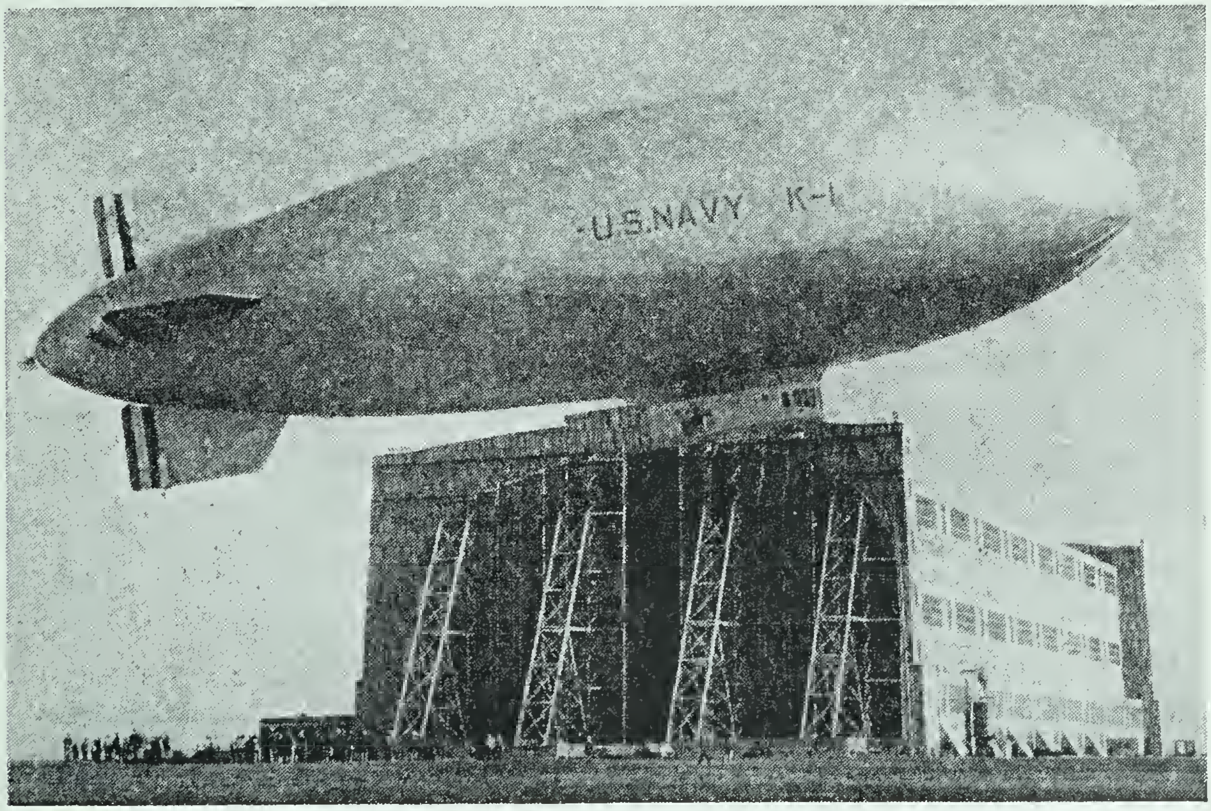
Courtesy Newark Museum — Photo by Bennett

Fig. 13–3. Granite and gneiss are both rocks which are mixtures. Each one contains at least three different minerals. On the left is a piece of rough granite; polished granite is in the center; and on the right is a piece of gneiss.

Some of our large dictionaries define almost a half million words, all formed from the 26 letters of our alphabet. Try to imagine the number of compounds it would be possible to make from 92 elements. But just as some letters do not combine well with others to form words, so some elements do not unite readily with others to form compounds. Half a dozen are known which never form any compounds at all. There are enough elements that do combine, however, to form the *several hundred thousands of compounds* known to chemists. Water, table salt, sugar, marble, alcohol, baking soda, ether, glycerine, turpentine, starch, nitric acid, and sulfuric acid are examples of some of the compounds used by chemists.

Why do we need to learn special properties? If all substances had the same odor and taste, and looked alike, we would have a hard task telling one from another. Since they do differ, however, in some *special* properties, we can learn to identify them. For example, no one can ever forget the odor of ammonia, but it would be impossible for him to describe that odor to someone who had never smelled ammonia. Alcohol is another substance with so peculiar an odor that its odor can be used for its identification. Table salt may be identified by its taste, but the tasting of chemicals in a chemical laboratory is not recommended as a means of identification.

We use copper for electrical wires because copper is the best conductor of electricity known, except silver which is too expensive to use for that purpose. We like aluminum for cooking utensils because it is durable, light, a good conductor of heat, and rather easily kept clean. Hydrogen is the lightest gas known; hence it is efficient when used for filling balloons. However, hydrogen burns easily. For that reason, helium, which lifts only 93% as much weight as an equal volume of hydrogen, but is not flammable, is



Official Photo U. S. Navy

Fig. 13–4. A United States Navy dirigible in front of a hangar. Its gas bags contain helium.

now being used to fill dirigibles. (See Fig. 13–4.) Arsenate of lead is used to kill insects because it is poisonous, yet it is not likely to injure the plants.

What distinguishes physical properties from chemical properties? We have already learned two reasons for studying properties, namely: (1) for identification; (2) to determine usefulness. Such a study will be easier if the student follows a definite order in listing properties, and keeps *physical* properties distinct from *chemical* properties.

Under physical properties of gases we include *color, odor, taste, solubility in water,* and the *relative weight* of the gas as compared to air or to hydrogen. In the case of metals and other solids or liquids, we list also such properties as *hardness, relative weight* as compared to water, *conductivity of heat and electricity, tenacity, ductility,* and *malleability.*

Under chemical properties we include *chemical activity,* or behavior with other substances. Some substances are *active,* combining readily with others. Some other elements are *inert,* or *inactive.*

What is a physical change? Ice melts, water changes to steam, liquids freeze, glass breaks, and sugar dissolves in water. We may magnetize a piece of steel, or pass an electric current through a copper wire. In all these cases the matter undergoes some change. Its form may be different, or its state may have been changed, but in no case has the matter lost its identity. No new substance is formed in any of these cases. *These are examples of physical changes,* because in no case is the molecule, or the physicist's unit, broken up. *Physics is defined as that science which deals with physical changes in matter. Any change in matter which does not destroy the identity of a substance, or change its characteristic properties, is a physical change.*

What is a chemical change? Wood burns, iron rusts, copper tarnishes, milk sours, plants decay, and acids interact with metals. In each of these changes, the identity of the original substance or substances is lost, and new substances with new properties are produced. *These are examples of chemical changes.* In some cases the original molecule is broken up into simpler molecules or into its atoms. In other cases, the atoms of two elements may have united to form a compound. In some chemical changes, too, the atoms rearrange themselves in the molecules, thus forming a new substance with decidedly different properties. *Chemistry is defined as that science which deals with chemical changes in matter; it also includes a study of elements and compounds.*

How can one bring about a chemical change? The chemist may use several agents to bring about a chemical change or to hasten one that has already started. Some type of energy is often used:

(1) *Heat energy.* We kindle a match head by rubbing it over some rough substance in order to warm it by friction. If we apply the lighted match to a piece of paper, the paper begins to burn. The heat from the burning match is used to start this chemical change. All of us are familiar with the *chemical changes caused by heat energy* during the baking of bread or cake or in the cooking of other foods. As a rule, increasing the temperature hastens the speed of chemical changes. An increase in temperature of 10° C. just about doubles the speed of a chemical reaction. For that reason, a food placed in boiling water at 100° C. will cook in about half the time that it does in a fireless cooker at 90° C.

(2) *Light energy.* If we open the shutter of our camera for only a fraction of a second, light enters and starts a chemical change on the film or plate. The colors of some rugs, draperies, or clothing may change, or even fade in sunlight. Some chemicals must be kept in dark-colored bottles to prevent their being changed by the action of light energy upon them. If you previously have studied biology you know the green leaves of plants can make starch out of the raw materials obtained from the air and the soil water, provided the leaves are exposed to sunlight. Plants cannot make starch in the dark. In fact, the green color of the leaves of a plant soon fades out if the plant is kept in the dark.

(3) *Electrical energy.* If one passes an electric current through water which contains a little acid in solution, the water will be decomposed by the electric current into hydrogen and oxygen. We make use of this method of bringing about a chemical change

when we charge a storage battery. Many compounds, if melted or if dissolved in water, can be decomposed by passing an electric current through the molten mass, or through the water solution. Electricity is also used commercially to produce chemical changes in the plating of one metal on another one, in the extraction of aluminum and other metals from their ores, and in the purifying of some metals.

(4) *Solution in water.* Baking powder is a mixture of two or more compounds. No chemical action occurs as long as the powder is kept *dry.* What do you observe when you put a half-teaspoonful of baking powder in a glass of water? Chemical action starts immediately, and a gas begins to bubble off. Many chemicals which do not react in the dry state begin to interact as soon as they are dissolved in water.

What are some proofs that chemical action is taking place? It is an interesting fact that several of the forms of energy which are capable of bringing about chemical changes are also evident during the change. For example, external heat must be used to start the burning of coal, but heat energy is set free as long as the coal continues to burn. *Any chemical reaction which liberates heat energy as it proceeds is called an exothermic (giving-out-heat) reaction.*

In the burning of coal, *light energy* is set free, too. From these two examples, we see that the evolution of heat energy and light energy are proofs that chemical action is taking place. Many other examples might be given.

The *mechanical energy* which is produced when dynamite or nitroglycerine explodes, and also the heat and light that are produced at the same time, are evidences of chemical action. The explosion of gunpowder, and of gasoline vapor in a gas engine are further examples.

In a dry cell, the zinc cylinder which is used as the negative plate of the cell, is acted upon chemically. As a result of such action and as proof that it is taking place, it is possible to get *electrical energy* from such a cell. In this case, chemical energy is used to produce electrical energy.

When water is added to baking powder, the gas carbon dioxide is set free. The *evolution of a gas* is often used as evidence that some chemical action is taking place. In many cases, a solid is formed by adding one solution to another one. The *formation of such a solid,* which is called a *precipitate,* furnishes evidence that a chemical change is taking place.

During some chemical changes, heat is absorbed all the time that the reaction is taking place. *Any reaction which absorbs heat as it progresses is called an endothermic (taking-in-heat) reaction.*

DEMONSTRATION. How can we distinguish between physical changes and chemical changes? Perform the following experiments:

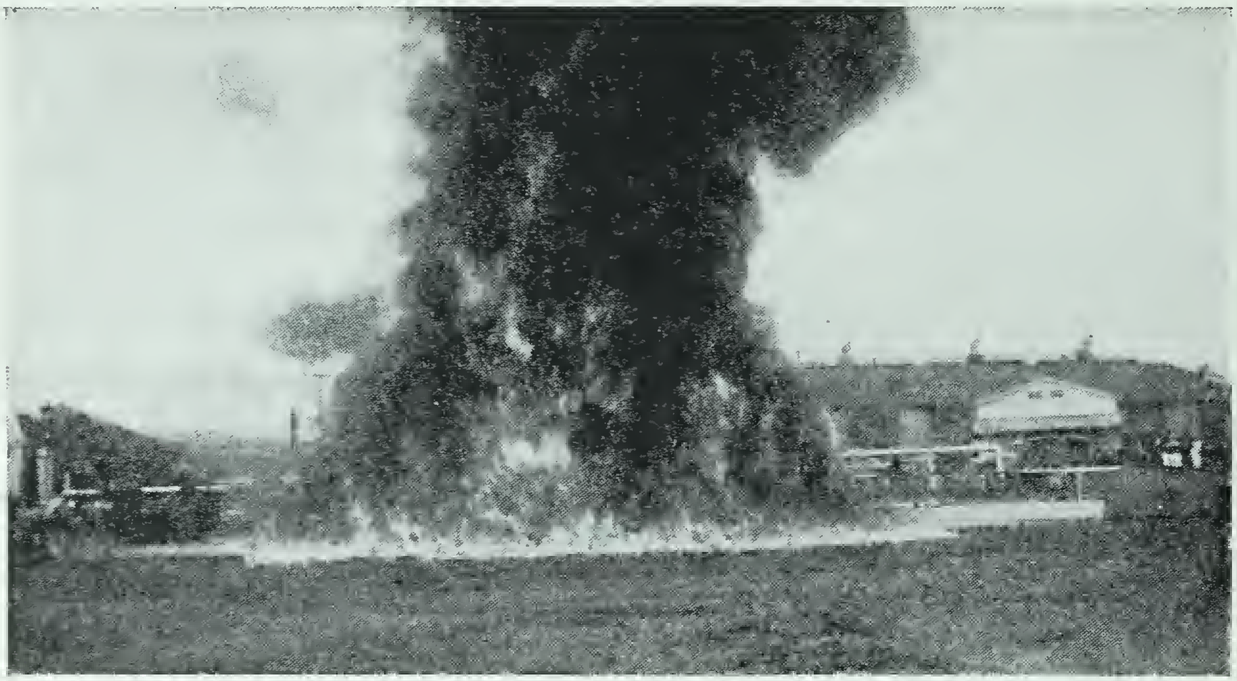
1. Break a wood splint into small pieces.
2. Burn a wood splint.
3. Add some water to some baking powder in a beaker.
4. Taste some salt crystals. Grind them and taste again.
5. Add some concentrated sulfuric acid to two teaspoonfuls of granulated sugar in a beaker.
6. To one-eighth of a test tube of concentrated nitric acid add a small strip of copper.

Which experiments brought about physical changes? Which brought about chemical changes? How did you tell?

2. CONDITIONS FOR COMBUSTION

What is meant by combustion? If we hold a piece of magnesium ribbon in the flame of a burner, it will ignite and burn with an intense white flame. It unites with oxygen so rapidly that both light and noticeable heat are produced. *Any chemical action which occurs so rapidly that both noticeable heat and light are produced is called burning, or combustion.* (See Fig. 13–5.) When wood burns, the carbon and the hydrogen of the wood unite chemically with the oxygen of the surrounding air. Ordinary *combustion is rapid oxidation in which heat and light are given forth.*

Three things are essential for any kind of combustion or burning: (1) a fuel, such as coal, oil, gasoline, or gas; (2) oxygen as a supporter of burning; and (3) sufficient temperature to start the burning.



Courtesy Pyrene Manufacturing Co.

FIG. 13–5. Combustion is rapid oxidation, so rapid that both heat and light are given forth.

Some substances burn and others do not. Some substances burn very readily. They are called *flammable*[1] substances. Some other substances, however, do not burn under ordinary circumstances; these are spoken of as being *incombustible.* All fuels contain carbon and hydrogen. Many of them also contain oxygen, which, as we have learned, is necessary for combustion, although it need not be present in the fuel itself.

Where is oxygen found? If you wanted to get away from oxygen, you would have a hard task, for it is the most abundant element known. About 20% of the atmosphere in which we live is oxygen. The animals that live in water get their oxygen from the small amount of the gas that dissolves in water; even water itself is a compound which contains almost 89% oxygen. Such minerals as clay, sand, and limestone contain a large percentage of oxygen.

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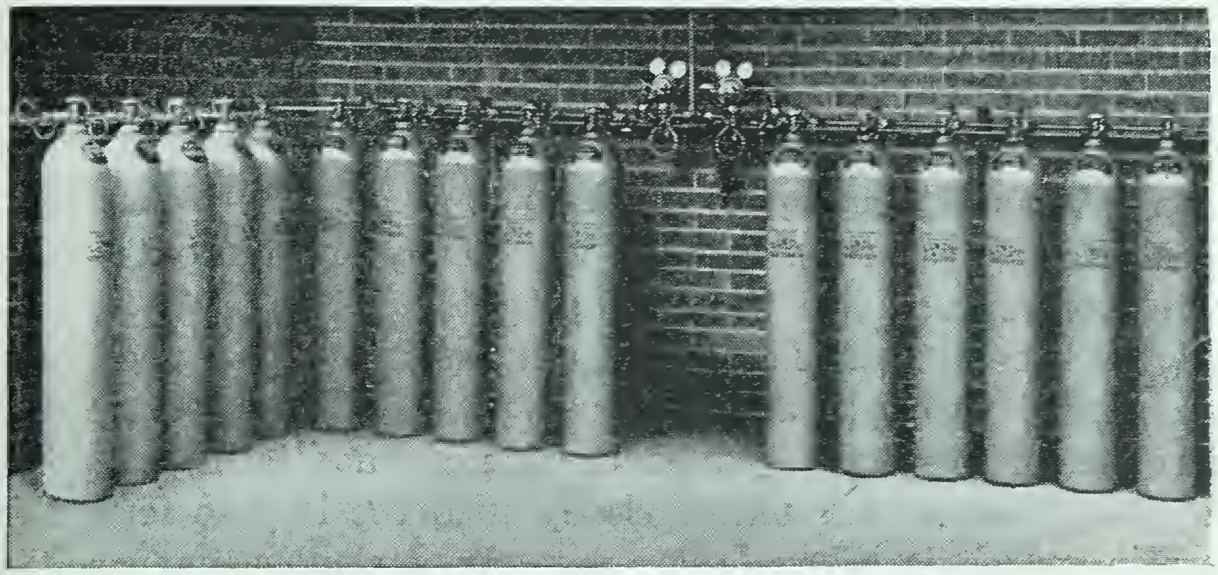
[1] Strange as it may seem, the words *flammable* and *inflammable* both have the same meaning. A foreigner learning English would suspect that the word *in*flammable means *non*combustible. Such an error has been the cause of accidents in industrial plants. For that reason the Bureau of Standards is trying to have the word *flammable* used in marking all combustible materials.



Courtesy Linde Air Products Co.

FIG. 13–6. Gases are bulky. Most of them are compressed into steel cylinders for the market. These cylinders contain oxygen under pressure.

What are the physical properties of oxygen? Pure oxygen is a colorless, odorless, tasteless gas which is slightly denser than air. At standard conditions of temperature and pressure, one liter of oxygen weighs almost 1.43 grams. Under the same conditions, one liter of air weighs 1.29 grams. Oxygen is slightly soluble in water, but 100 liters of *ice* water will dissolve nearly five liters of oxygen gas at standard pressure. It is interesting to note that 100 liters of water at room temperature, about 20° C., can dissolve only slightly more than three liters of oxygen at standard pressure. Therefore, if 100 liters of ice water, which is saturated with oxygen gas, is warmed to room temperature, about two liters of oxygen gas will be expelled. This explains why bubbles of gas appear on the inside of a glass of ice water which is permitted to stand for some time in a warm room. About one-third of each gas bubble is oxygen. All gases are less soluble in warm water than they are in cold water. Any gas may be converted into a liquid, if it is put under a very high pressure, and cooled sufficiently at the same time. Oxygen may be converted into a liquid which is pale-blue in color. Liquid oxygen is slightly attracted by a magnet. Does that not seem to be a curious property? Oxygen is marketed as a compressed gas. (See Fig. 13–6.)

How does oxygen behave chemically? Oxygen has been called an affectionate element; it combines readily with many other elements. The most important chemical property of oxygen is its *activity.* At ordinary room temperature, oxygen may act *slowly* with substances, and in some cases not at all. At higher temperatures, oxygen reacts *rapidly* with many substances, usually with the evolution of both heat and light.

What is oxidation? Let us scrape the surface of a piece of sheet lead until it is bright and lustrous. In a few minutes, we find that the surface of the lead has become dull and tarnished. The oxygen of the air has united slowly with the lead to form this tarnish, which is called *lead oxide.* In a similar manner, the oxygen which we take into our lungs in breathing unites with the carbon and hydrogen which are present in our foods and oxidizes them, or converts them into oxides. The carbon and oxygen unite to form carbon dioxide, which has the formula CO_2, and the hydrogen unites with the oxygen, forming water, or hydrogen oxide. In all these cases, heat is evolved, but no light is produced. In such a manner, the temperature of the normal, healthy human body is kept at 98.6° F., summer or winter. The decay of wood and vegetable matter, and the rusting of certain other metals, are other examples of *slow oxidation.* We may define oxidation as *that process by which oxygen unites with some other substance.* The product formed by oxidation is called an *oxide.*

What is a supporter of combustion? Air does not burn, but substances burn in air. We say that the air *supports combustion.* Substances burn more rapidly in oxygen than they do in ordinary air, and some substances burn in oxygen which do not burn in air at all. Hence oxygen is a better supporter of combustion than ordinary air. Magnesium burns in air, but it burns almost explosively in oxygen. Finely divided iron burns in oxygen, giving off dazzling white sparks.

How do we test for oxygen? A blazing splinter continues to burn in air, but it burns more vigorously in pure oxygen. If one takes a blazing splinter, extinguishes the flame so that only a *glowing spark* remains, and then lowers the glowing splinter into a bottle of oxygen, it will burst into flame immediately. *This test serves to identify oxygen.*

DEMONSTRATION. How can we test for oxygen? Fill the curved portion of the bottom of a Pyrex test tube with mercuric oxide powder. Heat the tube in the flame of a Bunsen burner until a silvery gray deposit begins to appear about the middle of the test tube, then insert a glowing splint into the mouth of the tube. Note the result. Do you think oxygen was present? Why?

What is meant by kindling temperature? The furniture of your room is made of combustible material, and it is surrounded by air containing oxygen. Why doesn't it burn? Before wood or other combustible material can begin to burn, heat must be applied to warm it up to its *kindling temperature. The lowest temperature at which a substance takes fire, or begins to burn, is called its kindling temperature* or ignition temperature. For flammable substances like gasoline, benzene, and alcohol the ignition temperature is called the *flash point.*

Different substances have different kindling temperatures. We may demonstrate this fact by pouring into one 100-c.c. beaker about 10 c.c. of carbon disulfide, into another beaker an equal amount of alcohol, and into a third beaker an equal amount of gasoline. Next we warm a glass rod in a burner flame and then hold the rod in the vapor above each liquid. If no one of them ignites, heat the rod a little hotter. You will find that the vapor of each liquid has a different kindling temperature.

The warmth of the hand is sufficient to kindle phosphorus, but you must not try it, because phosphorus produces frightful burns! The head of a match is made of some low-kindling-temperature material. When the head is ignited by the heat caused by friction, it sets free enough heat as it burns to kindle the matchstick. (See Fig. 13–7.) The reaction is exothermic.

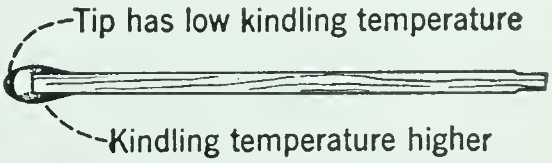


FIG. 13–7. A longitudinal section of a match. Can you explain the reason for the method of its construction?

How does increasing the amount of surface affect the rate of combustion? It is not difficult to show that combustion occurs at the surface *only* of the burning material. Let us support a match head on the top of the tube of a burner. Then we turn on the gas and light it. (See Fig. 13–8.) The fact that the match is not kindled shows that the flame is hollow and that burning is taking place only at the surface where the gas comes into contact with the air. This fact may also be shown by momentarily thrusting a sheet of paper down upon the flame. The charred spot on the paper will be circular with an uncharred spot in its center.

If we split a block of wood into two pieces, we produce two new surfaces at which combustion may take place. Such pieces will burn faster than a single block. If these pieces are split again, more new surfaces are exposed to the oxygen of the air, and combustion is still more rapid. Wood shavings, excelsior, and paper burn rapidly because they have such large surface areas at which combustion can occur.

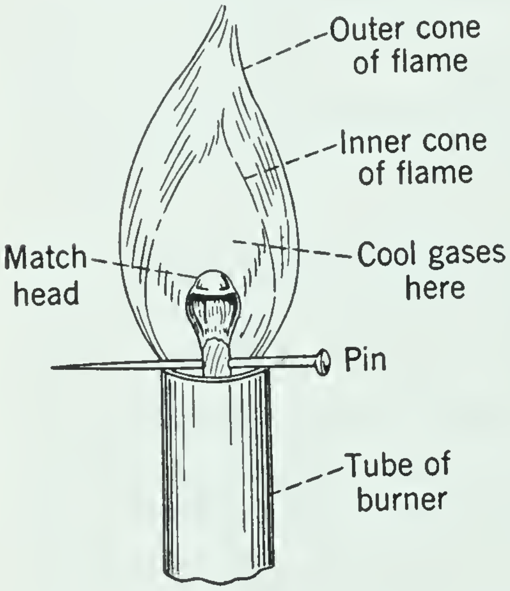


Fig. 13–8. The unburned match shows that combustion occurs at the surface only, where the gases are uniting with oxygen.

Since combustion occurs only at the surface, it is obvious that increasing the surface area will increase the rate at which a substance burns.

Demonstration. Place a circular piece of metal on the ring of a ring stand. Place some bits of paper, wood, sulfur, coal, and red phosphorus in a circle about four or five inches in diameter. Place a Bunsen burner under the center of the metal disc and heat until each sample of material has become ignited. List these substances in order of increasing kindling temperature.

In a similar manner, compare the kindling temperature of fuel oil, kerosene, and gasoline by placing a few drops of each on the metal plate and heat with a Bunsen burner.

Can combustion occur spontaneously? Is it possible to have a fire which is a self-starter, or a fire which starts without being set? The following kinds of material are favorable for spontaneous combustion:

1. *Material which has a low kindling temperature*
2. *Combustible material which oxidizes at ordinary temperature*
3. *Material enclosed in a box, a basket, or a corner of a room where the circulation is so poor that it does not carry away the heat produced by the oxidation of the material*

Let us place a piece of white phosphorus about as large as a pinhead upon an asbestos board. We can tell from the white fumes that arise that oxidation is taking place. Next let us cover the phosphorus with a half-teaspoonful of animal charcoal, or boneblack. The boneblack keeps most of the heat caused by oxidation from escaping, and in a few minutes the phosphorus will take fire.

Many fires start from spontaneous combustion. To prevent fires of that kind, metal cans should be provided for oil-soaked wiping cloths. Soft coal is sometimes stored under water. If hay that has not been well cured (too green) is stored in a barn, it may take fire from spontaneous combustion. Vegetable oils and some animal oils absorb oxygen slowly and may take fire spontaneously. Linseed oil, for example, "dries" by absorbing oxygen and forming a leathery skin, or film. For that reason, rags used by painters for wiping their hands or for wiping up spilled paint are particularly dangerous, and after such use they should always be thrown into a metal can or out-of-doors where there is a good circulation of air.

What principles are used in extinguishing fires? Let us keep in mind the fact that three things are needed before combustion can occur:

1. *A supply of combustible material*
2. *A supply of oxygen*
3. *A substance heated to its kindling temperature*

Naturally, if we eliminate any one of the three things just mentioned, the fire will be extinguished. In all of the methods in use for extinguishing fires, at least one of three principles is applied:

1. *Removing the combustible material*
2. *Shutting off the supply of oxygen, by blanketing, for example*
3. *Cooling the burning substance below its kindling temperature*

Let us mention some examples of each principle. Just as it is possible for you to remove some fuel from an overheated furnace, so material may be removed to prevent the spread of a large fire. Those of you who saw the motion picture *San Francisco* will recall how buildings were dynamited to prevent further spread of a city fire. Buildings are sacrificed by being torn down in heaps so that they will not burn well. Backfiring of prairie grass, and the removal of trees and underbrush from forested slopes to make firebreaks are other examples. (See Fig. 13–9.) Water lowers the

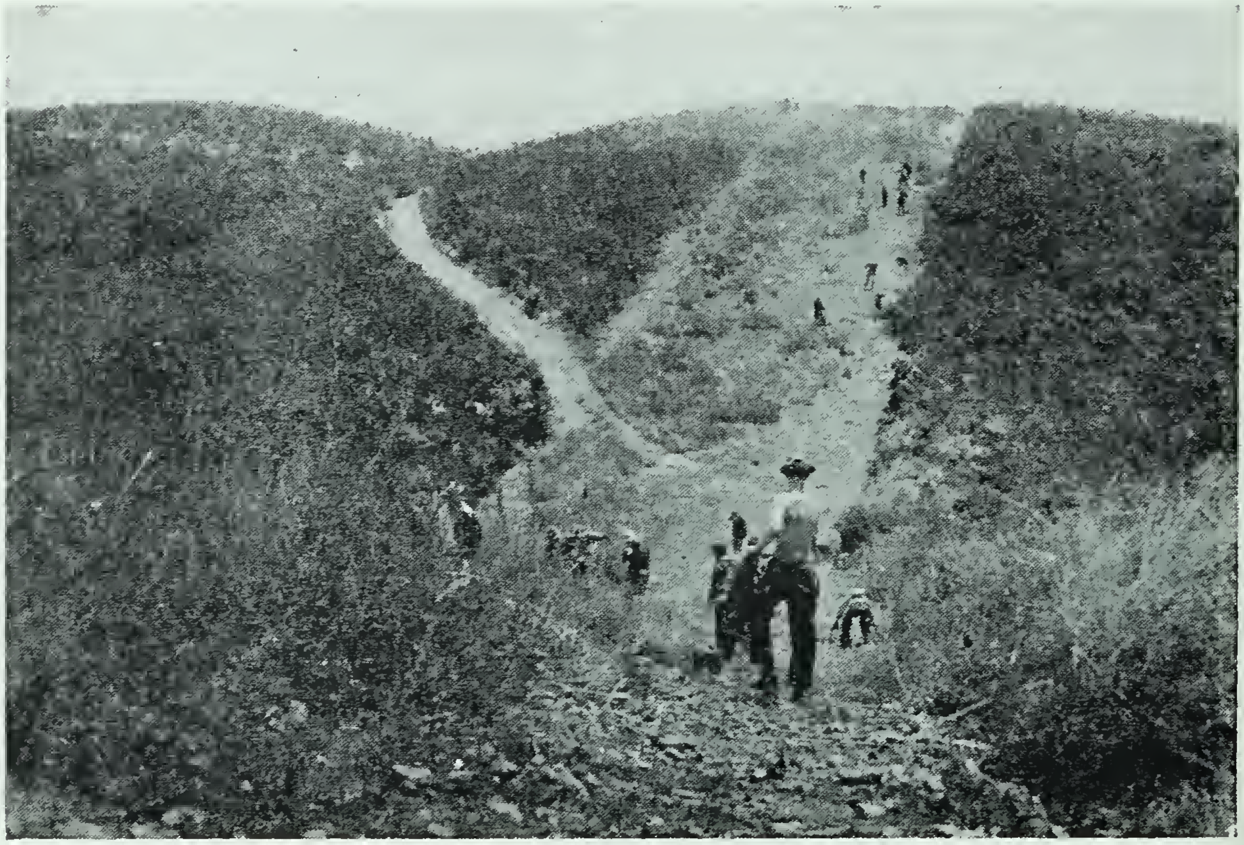


Photo by U. S. Forest Service

FIG. 13–9. Clearings known as firebreaks are made to prevent the spread of forest fires.

temperature of the burning substance, and, as the water evaporates, its vapor shuts off the supply of oxygen. (See Fig. 13–10.) The vapor formed from water takes up about 1700 times as much space as the liquid water had occupied. The effect of lowering the temperature may be shown by holding a copper spiral in a candle flame. The copper conducts away the heat so rapidly that the temperature falls below the kindling point, and the flame is extinguished.

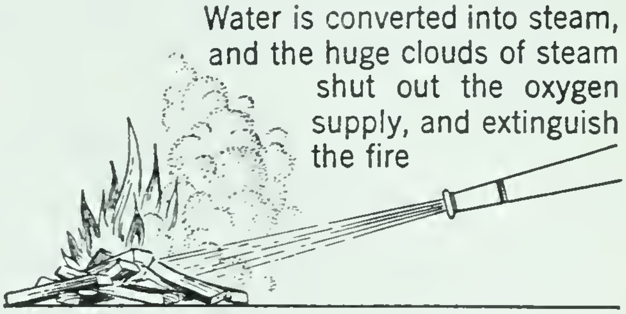

Water is converted into steam, and the huge clouds of steam shut out the oxygen supply, and extinguish the fire

Fig. 13–10. Part of the water used to extinguish a fire is converted into steam. The large volume of steam smothers the fire.

In time of war, magnesium is used in incendiary bombs. It is very difficult to extinguish burning magnesium, which is hot enough to decompose carbon dioxide and then unite almost explosively with the oxygen thus set free. Water thrown upon burning magnesium scatters it about and may thus start fires in other places. It may be covered with dry sand, or it may be caused to burn out more quickly by spraying upon it a fine mist of water. From a distance a stream of water may be used.

3. PRODUCTS OF COMBUSTION

Are oxides important compounds? Such metals as tin, lead, copper, zinc, and iron unite with oxygen to form oxides, either slowly when cold, or more rapidly when heated. Hydrogen unites with oxygen to form water, which is an oxide. Carbon unites with oxygen to form carbon *di*oxide (CO_2) when there is an excess of oxygen present, or to form carbon *mon*oxide (CO) when the carbon is present in excess.

What are the products of ordinary oxidation or burning? When you blow your breath through a clear solution of limewater, a milky white precipitate is produced. This reaction, which is caused by the interaction of limewater, $Ca(OH)_2$, and the carbon dioxide from your breath, is a *test for the presence of carbon dioxide,*

CO_2. The precipitate formed is calcium carbonate. The carbon dioxide was formed by the slow oxidation of carbon which was present in certain foods in your blood.

If you blow your breath against a cold window pane, water condenses upon the glass. The water, too, was formed by the "slow fires" burning at all times in living bodies. Slow oxidation and combustion differ only in the speed at which they occur.

Illuminating gas contains hydrogen and carbon. When it is burned, it forms carbon dioxide and water. A wax candle, wood, coal, and such fuels as gasoline and kerosene are composed largely of carbon and hydrogen. When these elements in the fuels burn, both water and carbon dioxide are produced. The mineral matter present in wood and coal is left as an ash when the fuel burns, and small quantities of other products are sometimes formed.

If there is not enough oxygen to burn all the carbon in a fuel to form carbon dioxide, some carbon monoxide, CO, may be formed, or even some particles of unburned carbon may be left as soot. Such *incomplete* combustion occurs when gasoline burns in a gasoline engine, or when fresh fuel is added to a furnace fire and a part of the oxygen supply is cut off by closing the draft. *Carbon dioxide is nonpoisonous, but carbon monoxide is a deadly poison.*

DEMONSTRATION. Burn a short candle in a wide-mouthed bottle containing some limewater. Cover the mouth of the bottle with a plate of glass until the flame goes out. Note the film of moisture formed on the bottom of the glass plate. Place the palm of the hand over the mouth of the bottle and shake vigorously. Note any color change in the limewater. (Carbon dioxide gas turns limewater milky.) What two products of burning have just been identified?

Hold a glass plate against the tip of a candle flame for a few seconds. Repeat, using another glass plate held over burning gasoline in an evaporating dish. Compare the carbon deposits. Which flame illustrates the more complete burning?

What changes in weight occur in burning? When you burn wood or coal, the solid ash that is left weighs much less than did the original material. If, however, you could collect all the water vapor, the carbon dioxide, and other gases which go up the chimney when coal burns, weigh them, and add their weight to the weight of the solid ash, you would find a decided increase in weight. In fact, when one ton of pure charcoal is completely burned, it unites with two and two-thirds tons of oxygen and forms three and two-thirds tons of carbon dioxide, which may escape up the chimney. The equation

$$C + O_2 \rightarrow CO_2 \uparrow$$

is typical of all chemical reactions. The total weights of the factors on the left side of the equation, carbon and oxygen in this case, exactly equal the total weight of the carbon dioxide as shown at the right side of the equation. In other words, *no weight is ever gained or lost in a chemical reaction,* a fact which is known as the LAW OF THE INDESTRUCTIBILITY OF MATTER.

Why is it that some substances do not burn? We have learned about flammable and incombustible substances. If we examine the formula for water, we see that the hydrogen holds all the oxygen that can be added to it by burning the hydrogen. Water is really the "ash" formed by burning hydrogen. Nearly all oxides are incombustible for the same reason. Carbon monoxide is an exception; it burns because each molecule of carbon monoxide, CO, can unite with another atom of oxygen. Water and carbon dioxide make excellent fire extinguishers because they are incombustible. The oxides of calcium, magnesium, and silicon, which is sand, or SiO_2, make good material for lining furnaces and for fireproofing.

4. EXPLOSIVE MIXTURES

What causes explosions? If a powdered substance is loose enough so that oxygen can mix with it readily, it will burn almost instantly and explosively when ignited. Explosions are destructive because the air around them and the products formed by such rapid oxidation are heated so strongly and suddenly that they may expand to occupy a space several thousand times their original space. *One type of explosion is practically instantaneous combustion throughout the entire mass.*

Dust scattered through the air of a coal mine, tiny particles of cork dust in a linoleum factory, or particles of flour in a flour mill, may explode with terrific force if they are ignited or warmed to their kindling temperature. Powdered coal, if blown by compressed air into a furnace, will burn in much the same manner that gas does.

How may explosions be useful? Of course you know that tons of explosives are used in warfare. The farmer uses explosives for "blowing out" stumps when clearing his land, and sometimes for loosening compact subsoil. The road builder uses explosives for blasting away rocks in cuts and tunnels. Explosives have been used to break up extensive ice gorges and thus prevent the destruction of bridges which might have been carried away by the swollen rivers. In the engines of the more than 30,000,000 automobiles and trucks in the United States there may be some 30 to 60 explosions every second.

The carburetor of an automobile evaporates liquid gasoline and mixes the gasoline vapor with enough air to form an explosive mixture. (See Fig. 14–19.) As the piston in the cylinder of a gas engine moves downward, a valve opens and permits the explosive mixture to enter the upper part of the cylinder. There the mixture is compressed into a small volume as the piston moves upward. (See Fig. 14–6.) An electric spark then heats the mixture up to its kindling temperature and the mixture explodes, driving the piston downward with great force. Thus we use the force caused by the *rapid expansion of exploding gases* to drive the engine which, in turn, drives the automobile. On the next upstroke a valve permits waste gases to escape, and then the whole operation is repeated again and again.

Demonstration. Pour some lycopodium powder into a can and cover it with a friction lid. The side of the can should be fitted with a spark plug with induction coil and battery attachment. Shake the can to produce a dust of the powder; then close the switch. Note the result. If the spark plug attachment is not available light the dust mixture by means of a match held under a small hole in the bottom of the can.

Repeat the experiment, substituting fuel gas from the gas jet for the lycopodium. Result?

Explode gasoline in test tubes by dropping gasoline into them with an eye dropper. Vary the number of drops until the right mixture has been determined.

Proper mixtures important. In order to get as much heat as possible from a pound of fuel it is necessary to completely burn the fuel. The formation of carbon or carbon monoxide decreases the efficiency of that burner. In order to produce complete combustion it is necessary to have the proper mixture of fuel and oxygen.

The ideal mixture for a gasoline engine is 15 volumes of oxygen to 1 volume of gasoline vapor. This, in terms of volume, means that 1240 gallons of air is needed to burn 1 gallon of gasoline. Of course the gasoline must be completely converted to the gaseous state before it will explode in the cylinder of a car.

One of the main purposes of the carburetor of a car is to keep constant the right mixture of the vaporized gasoline and air.

B. GASOLINE AS A FUEL

1. ORIGIN OF GASOLINE

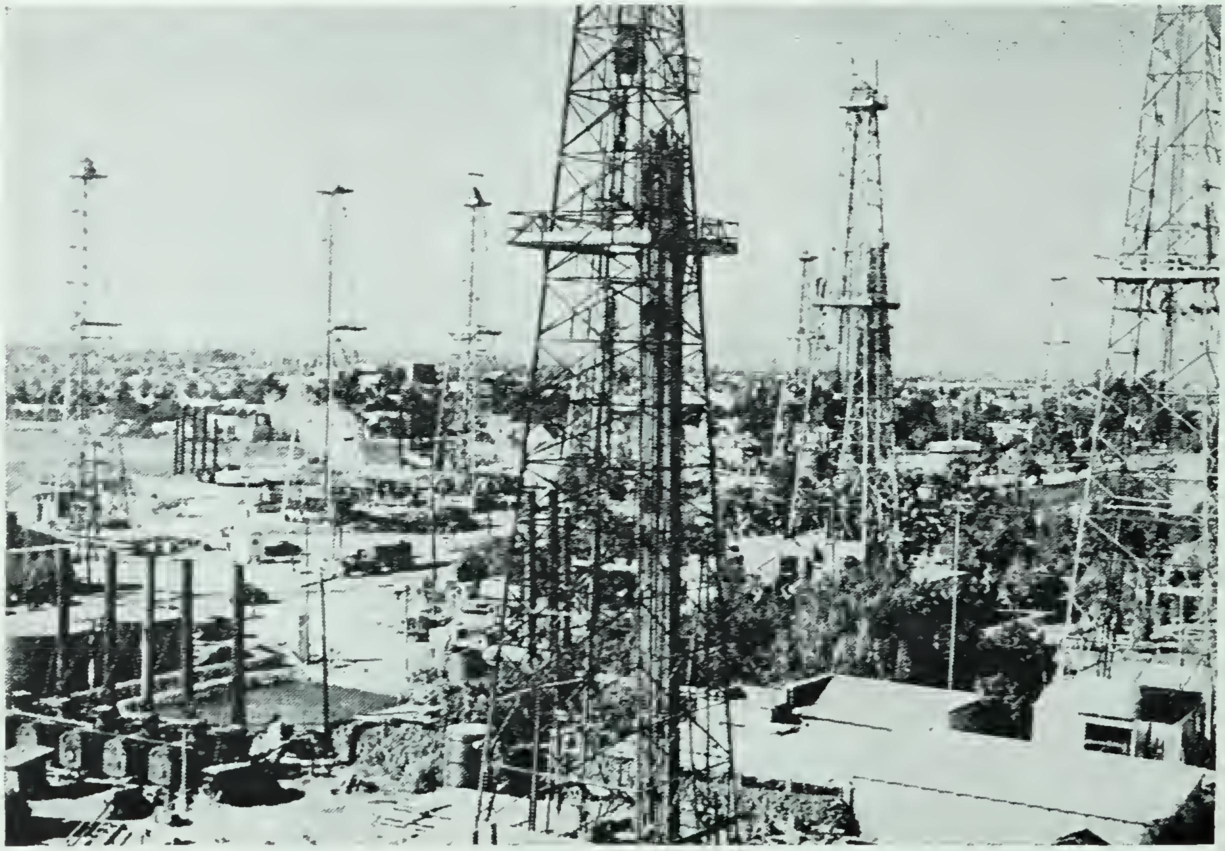
Gasoline is an organic substance. From the roots of the carrot, turnip, and beet we get food products. We get sugar from the sugar beet, from the stem or stalk of the sugar cane, and from the sap of the maple tree. The potato comes from an underground stem. We get camphor from the twigs or leaves of the camphor tree, turpentine and rosin from the long-leaved pine, and latex for making rubber from the milky sap of the India-rubber tree. Starch is present in many different kinds of grain. Many seeds contain oil, of which cottonseed and linseed or flaxseed are examples. Tea leaves contain tannin and theine, and the coffee berry contains caffeine. From even this very small number of examples, it is easy to understand why the *destructive distillation* of wood and vegetable wastes yields many organic products, or compounds of carbon.

Another source of carbon compounds is *coal*. Its destructive distillation yields many different products. Carbon compounds, too, are obtained by distilling *petroleum*, which is a very rich source.

What is petroleum? The liquid known as petroleum is a mixture of many hydrocarbons. It is usually rather thick, of a brown or greenish-black color. Although it was discovered in the United States some three hundred years ago, it was not until 1854 that the first company organized to drill for petroleum was formed.

Where is petroleum found? Our Machine Age demands petroleum for proper functioning. Modern warfare is so highly mechanized that petroleum is more important than ever. There is a rich supply in the Caucasus, not too far from the Caspian Sea. The oil fields of Iran are valuable, and so are those in Rumania. In South America, Venezuela produces petroleum. Mexico, too, is a producer of petroleum.

In the United States, oil was first produced in Pennsylvania. Then oil fields were opened in Ohio and West Virginia. Illinois,



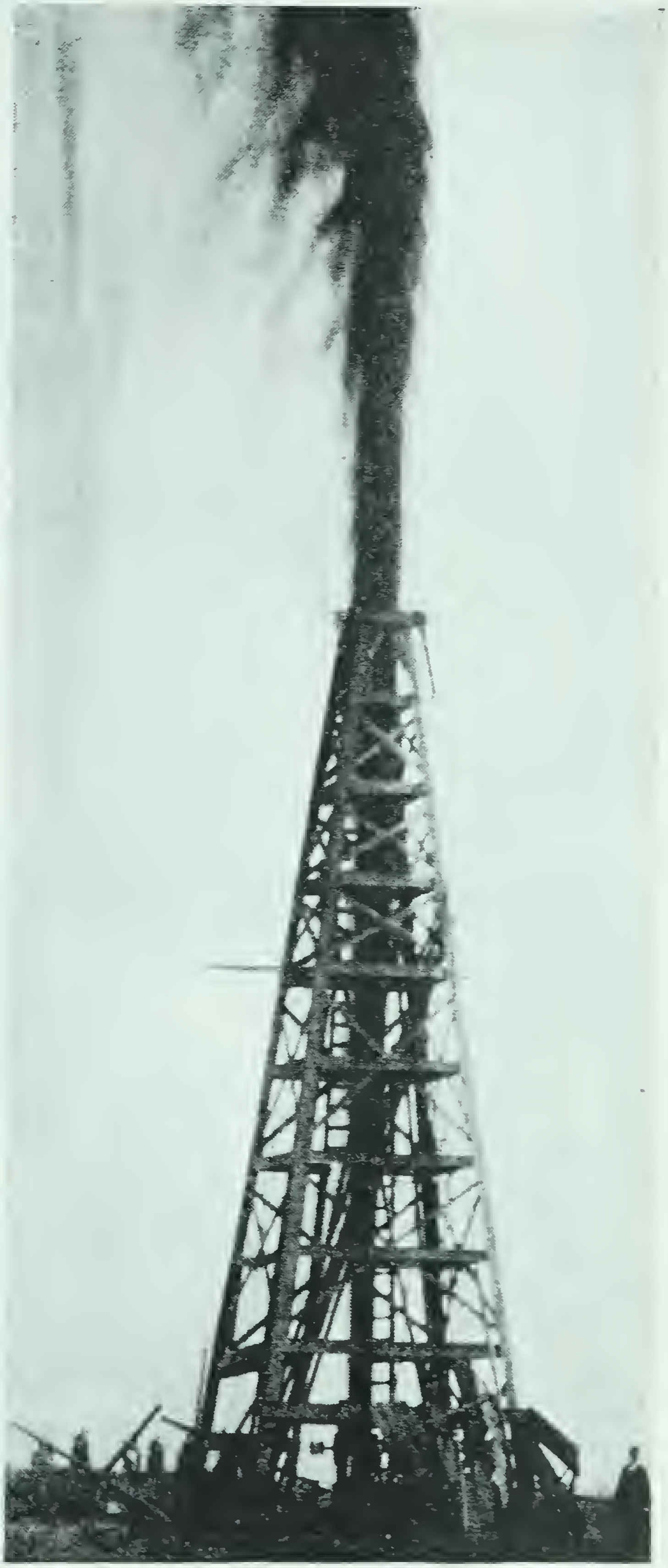
Courtesy American Petroleum Institute

Fig. 13–11. A general view of the derricks in an oil field.

Kansas, Oklahoma, and California produce oil in quantity. The oil fields in Texas seem to be among the richest found anywhere in the world. Oil is now being produced in Montana, and in Alberta, Canada. (See Fig. 13–11.)

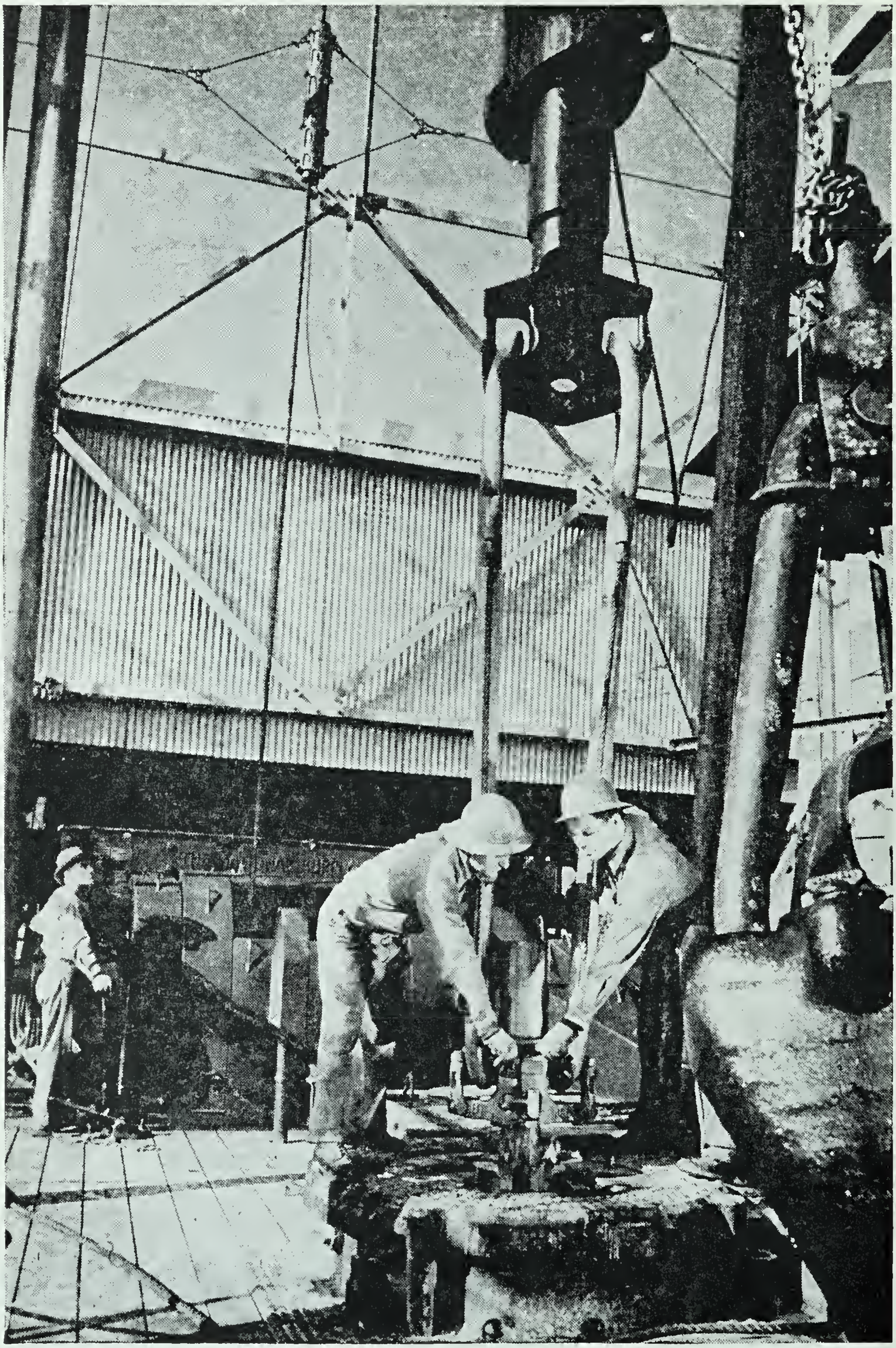
How is petroleum obtained? Petroleum may be found near the surface of the earth, at a depth varying from a few hundred feet to more than three miles. In some cases it seems to be present in *reservoirs* of oil-saturated sand or gravel, and in others it seems to form underground streams. To get the petroleum, holes from 6 in. to 8 in. in diameter are drilled down to the oil deposits. A huge piece of metal shaped like a cold chisel may be used as a drill, but in many cases a rotary drill is used.

If much natural gas is present with the petroleum, the crude oil is forced out of the well under pressure, forming what is known as a *gusher*. (See



Brown Bros.

Fig. 13–12. A gusher from which oil is forced by gas pressure.

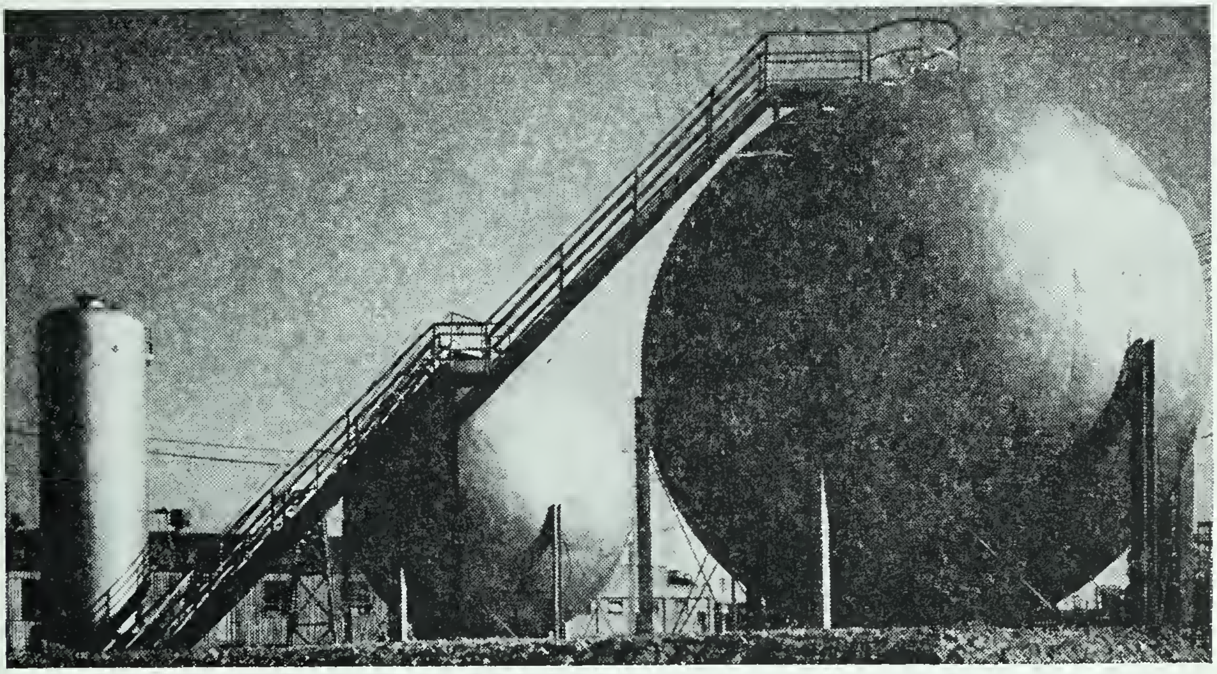


Courtesy Texas Co.

Fig. 13–13. The modern oil-well drill is a complicated mechanism.

Fig. 13–12.) Some gushers flow several hundred barrels of oil per day. Some wells contain nothing but natural gas; others produce nothing but petroleum; and still others produce both gas and petroleum.

If the oil does not rise in the well as far as the surface of the ground, pumps must be installed to pump the oil to a storage tank or to the refineries. (See Figure 13–13.) Some of the pipe lines through which petroleum or *crude oil* is pumped are fifteen hundred



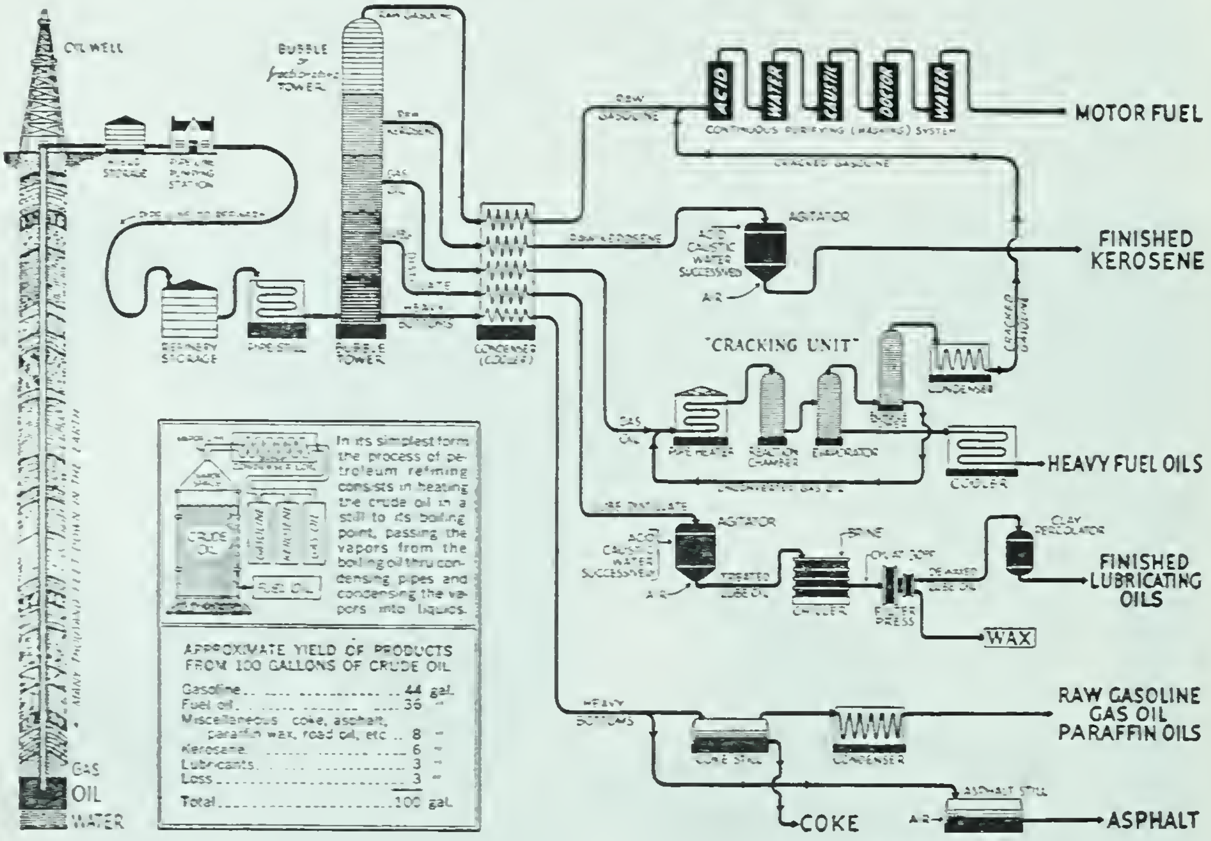
Esso Marketers Photo

Fig. 13–14. Petroleum products are stored in several ways. These unusually interesting spheres hold gasoline.

miles in length. (See Fig. 4–31.) They may extend from Texas or Oklahoma to the refineries in New Jersey. (See Fig. 13–14.)

How is petroleum refined? Since petroleum is a mixture of several liquid hydrocarbons which have different boiling points, they must be separated from one another in the refining process by the use of *fractional distillation.* Figure 13–15 shows how the petroleum is heated in a still or a bubble tower in order to vaporize the different hydrocarbons. The separate fractions, which have different boiling points, condense to liquids again as they are cooled in the condenser. For purification, the separate distillates are washed with sulfuric acid to char impurities; the acid is then neutralized with an alkali, and the product is washed with water.

Some of the products obtained from petroleum include *petroleum ether*, *gasoline*, *naphtha*, *benzine*, *kerosene*, *gas oils*, *lubricating oils*, *fuel oils*, *petroleum jelly*, *paraffin*, and *coke*.



In its simplest form the process of petroleum refining consists in heating the crude oil in a still to its boiling point, passing the vapors from the boiling oil thru condensing pipes and condensing the vapors into liquids.

APPROXIMATE YIELD OF PRODUCTS FROM 100 GALLONS OF CRUDE OIL

Gasoline	44	gal.
Fuel oil	36	"
Miscellaneous coke, asphalt, paraffin wax, road oil, etc	8	"
Kerosene	6	"
Lubricants	3	"
Loss	3	"
Total	100	gal.

Courtesy Socony-Vacuum Co.

Fig. 13–15. The various products are separated from petroleum by fractional distillation.

Demonstration. Set up an apparatus as shown in Figure 11–25 and distill some crude oil until 10 cc. of distillate has been collected. Test the distillate for flammability.

Compare the rates of evaporation of water, alcohol, gasoline, and crude oil by placing equal volumes of each in separate water glasses and observing at frequent intervals.

Examine samples of kerosene, benzol, alcohol, and fuel oil. What are the outstanding differences in physical properties?

How do refiners increase the yield of gasoline? During the closing decades of the nineteenth century, gasoline was more or less a drug on the market, and kerosene was in demand. Now conditions are reversed. Even as late as 1900 automobiles were few in number. Now there are more than 30,000,000 cars in the United States alone, almost all of them running on gasoline. The chemist's problem was to so refine petroleum that the yield of kerosene would be decreased and the yield of gasoline increased. Let us mention four methods:

(1) *The cracking process.* By referring to the table (Appendix A) we see that the hydrocarbons of low molecular weights are more volatile than those of higher molecular weights. For example, *heptane,* C_7H_{16}, which is present in gasoline, boils at 98° C. And *decane,* $C_{10}H_{22}$, which may be present in kerosene, boils at 173° C. It is difficult to vaporize decane, and it would be almost impossible to start a gas engine on a cold morning if one were using such a fuel. If, however, such heavy molecules are heated under pressure, they crack or split up into lighter molecules which are more easily vaporized. Such superheating is done in the *cracking* process of refining petroleum in order to increase the yield of gasoline from the petroleum.

(2) *Hydrogenation of hydrocarbons.* By calculating the percentage composition of both *heptane* and *decane* we find that the former contains almost 18% of hydrogen, and the latter a little more than 15%. Why not convert decane and other hydrocarbons of still higher molecular weights into more volatile compounds by the addition of hydrogen? That is exactly what is now being done. Refining plants are now in use for hydrogenating hydrocarbons by the aid of suitable catalysts.

(3) *Polymer gasoline.* It is possible to make a high-octane motor fuel by *polymerizing,* or "bunching" the simple molecules of such hydrocarbons as CH_4, C_2H_6, etc., in order to form molecules of greater molecular weight. They can be so made that they will vaporize at the proper temperature. Such gasolines are sometimes advertised as "poly" gasoline.

(4) *Casing-head gasoline.* The natural gas which escapes from gas wells consists largely of methane, but it also contains some other hydrocarbons. If it is cooled and compressed, the other hydrocarbons may be converted into a volatile liquid which serves as an excellent gasoline, especially for airplane motors. It vaporizes easily. Such casing-head gasoline may be blended with other gasolines, too.

Synthetic gasoline. Bergius, a German chemist of Heidelberg, devised a process for converting low-grade coal into gasoline and lubricating oils. The powdered coal is mixed with a viscous oil and heated in steel drums under a pressure of 200 atmospheres in the presence of the sulfides of iron, tungsten, and molybdenum as catalysts. When hydrogen is forced into the mixture, it unites with the carbon of the coal, forming light liquid hydrocarbons suitable for use as a motor fuel, and heavier oils suitable for use as lubricants. The value of this process is evident if we consider that the United States consumes more than twenty billion gallons of gasoline annually. England, like Germany, has built some plants for using the Bergius process as well. It is estimated that one ton of coal will yield 300 gallons of oil.

What are some uses of petroleum products? Three uses for petroleum products predominate:

(1) *As solvents.* *Petroleum ether* is a good solvent. *Gasoline, naphtha,* and *benzine* are mixtures of hydrocarbons which vary a great deal in composition. They are used to some extent as solvents. Painters sometimes use benzine as a substitute for turpentine.

(2) *As fuels.* *Gasoline, naphtha,* and *benzine* are important motor fuels, too, as well as solvents. *Kerosene* is used as a fuel or as an illuminant in localities not supplied with gas or electricity. It should have a *flash point* not lower than 110° F. if it is to be used in lamps with safety.

(3) *As lubricants.* A good lubricant must be mobile enough so it will have little internal friction. It should be viscous enough so it will not be squeezed out of the bearings by the weight of the parts. It must not decompose at the temperature at which it is used. The *lubricating oils* obtained from petroleum range from light, mobile oils suitable for use in a sewing machine to thick, viscous engine oils.

Vaseline and *petrolatum* serve as ointment bases, and as lubricants for use as cup grease and axle grease. *Paraffin* is used in making candles and as an electrical insulator. It is also used for waterproofing paper and fabrics.

Those portions of petroleum which have no lubricating properties and are not suitable for other uses are burned as *fuel oil.* Many persons now burn oil to heat their homes. Fuel oil is also much used instead of gas in certain industries, and for heating public buildings. Many of our battleships, cruisers, and destroyers are oil burners. *Petroleum coke,* the residue left after petroleum is refined, is an excellent fuel.

What efforts are made to make gasoline a knockless fuel? For several years, the refiners of gasoline have been adding *tetraethyl lead* to gasoline to prevent engine knocks. Its formula is $Pb(C_2H_5)_4$. *Ethylene bromide* is used with it to unite with the lead and prevent its being deposited on the points of the spark plugs. There seems to be less tendency for a high-compression motor to knock when using such a fuel. Tetraethyl lead seems to serve as a negative catalyst to retard the speed of combustion of the gasoline-air mixture and thus prevent knocking. A gasoline which contains a small quantity of tetraethyl lead and of ethylene bromide is called an *ethyl gas.*

The *octane number* of a gasoline is a term used to measure its tendency to knock when used as a motor fuel. It is a comparison based upon the qualities of *iso–octane* as a knockless motor fuel. For testing purposes a gasoline which is a mixture of *heptane* and *iso–octane* is usually used. Some of the regular gasolines contain about 27% of heptane to 73% of iso–octane, giving them an octane number of 73. Some of the better gasolines have only 15% of heptane and 85% of iso–octane, giving them an octane number of from 83 to 85. They work more satisfactorily than low-octane gasoline when the compression of the gasoline-air mixture is more than 6 to 1 before it is ignited. Commercial gasolines contain other hydrocarbons besides heptane and iso–octane.

2. REQUIREMENTS OF AN IDEAL GASOLINE

The ideal motor fuel. The ideal fuel must be sufficiently volatile to insure easy starting but not enough to form bubbles of vapor in the fuel system due to heat in fuel lines and carburetors. Such bubbles would stop the flow of gasoline. When the fuel enters the intake manifold from the carburetor it must be completely vaporized and uniformly mixed with air to allow equal distribution to all cylinders for quick and smooth acceleration.

For a given grade of gasoline one of the primary requirements is the greatest possible mileage per gallon, or low cost per mile.

Freedom from impurities is another requirement of the ideal gasoline. Two common impurities present in fuels are gum, which deposits on intake valves, and sulfur. When the latter burns, the resulting oxide (sulfur dioxide) in the presence of water in the form of superheated steam, and high pressure inside the cylinder form sulfuric acid which corrodes all metal surfaces with which it comes in contact.

Ideal power is that which pushes instead of hammering against a piston. If gasoline burns with a detonation it causes a knock or ping. Octane rating or antiknock rating ranges from 50 in third-grade gasolines to over 100 in aviation gasolines. Since a rating of 100 indicates a fuel having antiknock properties equal to pure iso–octane, more than 100 means an antiknock value superior to iso–octane. The higher the compression ratio of motors the higher the antiknock octane rating fuel required.

C. OTHER FUELS

1. LIQUIDS

Kerosene as a fuel. It may astonish you to learn that some persons living today can remember when the demand for kerosene far exceeded that for gasoline. Two changes in our way of living contributed to the reversal of those demands. The rise of the automobile multiplied manyfold the demand for gasoline. The more universal use of the electric light in place of the kerosene lamp reduced the demand for kerosene decidedly. Even fifty years ago, it was rather an unusual family that did not use at least five gallons of kerosene a week, and they probably used not more than a gallon of gasoline a year. Now the demand for kerosene, which is a petroleum product, is largely limited to small kerosene heaters and to those localities which do not have either natural or artificial gas. The odor of kerosene is unpleasant.

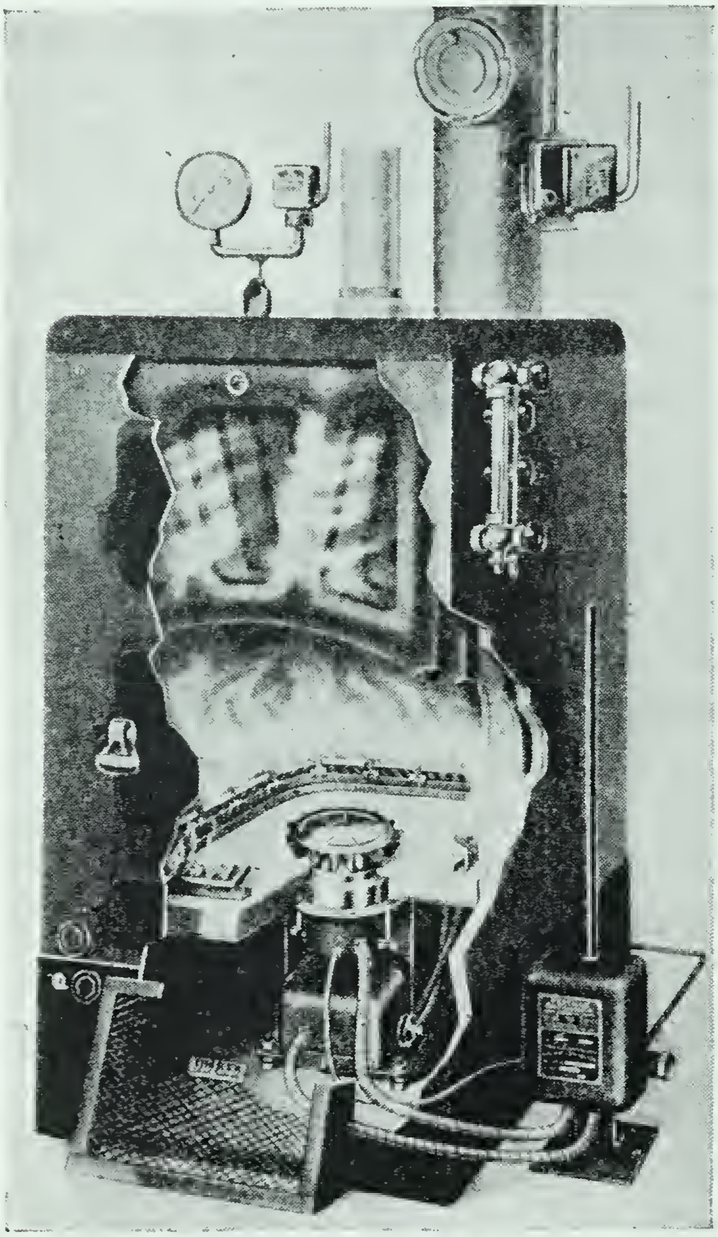
Benzol as a fuel. Benzol, a colorless liquid, a little lighter than air, and with a rather pleasant odor, is an excellent fuel for internal-combustion engines. Benzol was discovered in 1825 by Michael Faraday. It is a product of the destructive distillation of coal tar. Benzol is also known by the name of *benzene.* The term benzol is preferred however, because it prevents any possible confusion with benzine, which is a product of the distillation of petroleum. Benzol is sometimes blended with gasoline for use as a power fuel.

The use of power alcohol. *Ethanol,* or *ordinary alcohol,* burns with a clean flame, but it does not yield as many B.T.U.'s of heat per gallon as gasoline does. It gives satisfactory results as a motor fuel if it is blended with gasoline.

Alcohol can be made from many farm products, such as potatoes, rye, barley, wheat, and oats. It can be made, too, from such farm wastes as straw, oat hulls, cornstalks, and corncobs. For several years the Bureau of Agricultural Chemistry and Engineering in Washington, D.C., has had chemists at work in the Agricultural College at Ames, Iowa, on the problem of making alcohol and some by-products from farm wastes at a cost low enough to compete with gasoline. The center for this work is now located at Peoria, Illinois.

The Farm Chemurgic Group has been holding meetings at Dearborn, Michigan, under the sponsorship of Henry Ford. Several prominent chemists have been interested in advising farmers what crops to plant to avoid huge surpluses, and also in devising ways to utilize farm wastes.

The rise of the fuel oils. After the gasoline, kerosene, lubricating oils, and some other valuable products have been removed from petroleum by fractional distillation, some hydrocarbons which are not particularly suited for any other purpose are obtained for use as *fuel oils.* No one particularly enjoys taking care of a furnace in which coal is burned. The improvement of devices to atomize fuel oil, and of burners that will burn oil without danger of the formation of soot has contributed to the making of oil a desirable fuel, both for the home and the factory. (See Fig. 13–16.) A thermostat may be installed, and the control of an oil-burning furnace may be nearly automatic. There is no labor of stoking the furnace, and there are no ashes to be removed.



Courtesy Koppers Co.

FIG. 13–16. In such a burner, fuel oils are atomized so they will burn with little loss in fuel value.

The heat content of fuel oil is high, usually more than 10,000 calories per gram. The cost of installation, the interest on that amount of money, and the use of some electric current to operate the burner all contribute to make the use of oil for fuel rather more costly than hard coal, unless the coal must be transported long distances. In localities where fuel oil can be bought for about 7¢ per gallon, the cost is approximately the same as that of hard coal at $12.00 per ton.

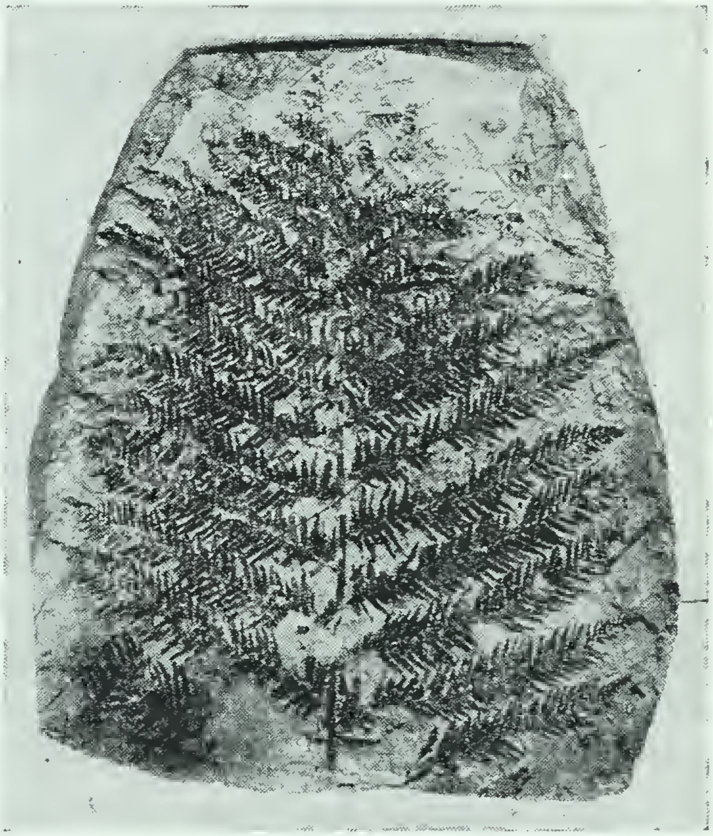
2. SOLIDS

Wood as a fuel. Probably no fuel is more widely distributed than wood. In localities where the cost is not too great, wood meets the demands for a good fuel, but its heat content is not very high. In localities where other fuels are used, wood is much used for kindling, and for fireplaces. An open wood fire in a room is a wonderful aid to cheerfulness.

What is peat? In Pennsylvania, Michigan, and Wisconsin *peat* bogs are found. They contain club mosses and other forms of vegetation which have undergone partial decomposition in marshy lands. In some places such deposits are several feet thick. Peat may be cut into blocks, and dried for use as fuel. Peat, which has long been used in Ireland as a fuel, burns with a smoky flame. It may be considered the first step in the evolution of coal.

What is lignite? In past geologic ages, several millions of years ago, vegetation on much of the earth was much more luxuriant than it is now, even in the tropical forests. In that *carboniferous* age, tree ferns, giant club mosses, and other forms of vegetation supplied the material for our coal deposits. Peat bogs were probably first formed. Then upheavals of parts of the earth's crust buried thick masses of vegetable matter beneath the surface of the earth. There it was subjected to increased temperatures and increased pressures.

At a fairly early stage in these changes, *lignite* was formed. It is not uncommon to find sticks, leaves, and branches in lignite; they furnish proof of its vegetable origin. (See Fig. 13–17.) Lignite, which is sometimes called *brown coal* from its brownish black color, is common in some of our western



American Museum of Natural History

Fig. 13–17. Sometimes leaves leave their "fingerprints" in coal, thus furnishing proof of their aid in forming coal.

states. It burns with a smoky flame, and it is inferior to soft coal in its heat content. Lignite disintegrates badly when stored.

Soft coal is a widely used fuel. *Bituminous coal,* which is commonly called soft coal, was probably formed from the fossil remains of prehistoric plants. Its origin is not so clearly shown as that of lignite, but it is not uncommon to find traces of plant remains in soft-coal beds. It appears to have been subjected to still greater heat and pressure than that encountered in the formation of lignite, and it may be considered as a third step in the evolution of coal. Soft coal has a higher per cent of carbon than does lignite, and it has a higher heat content. The map of Figure 13–18 shows that many states in the United States have rather extensive areas of coal.

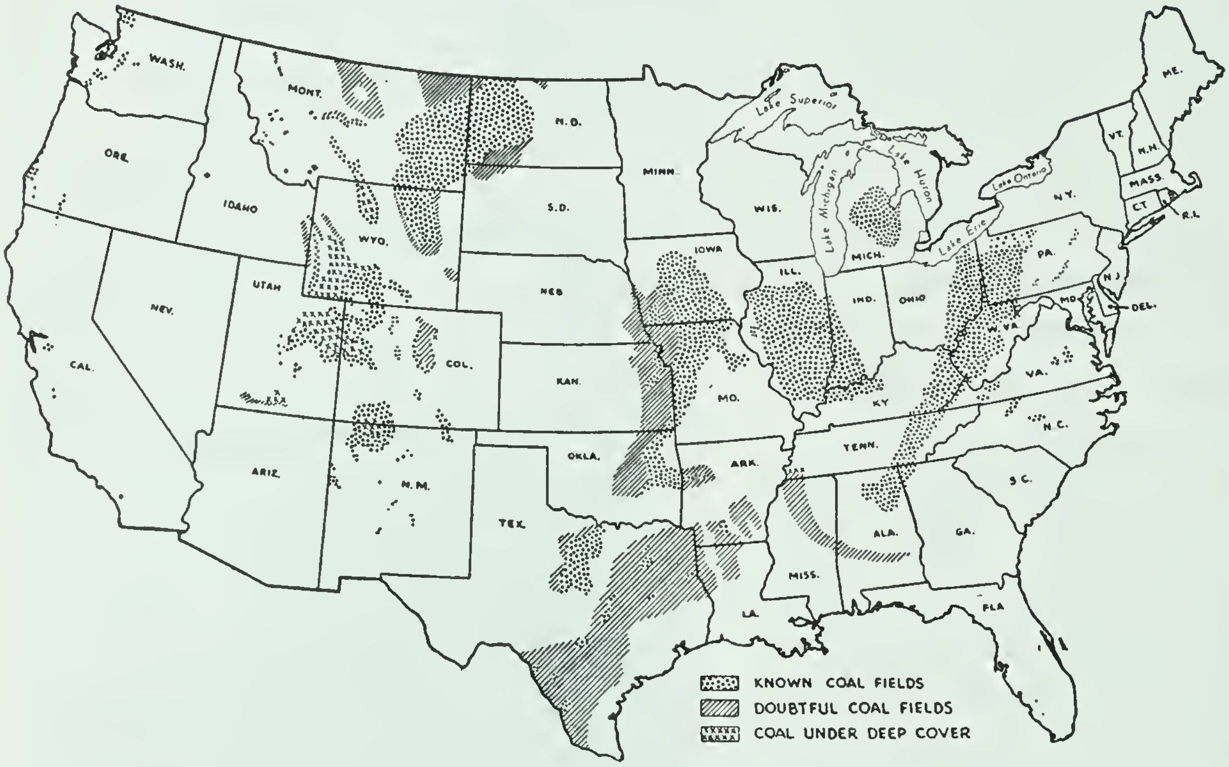


FIG. 13–18. This map shows the general distribution of the most important coal fields in the United States.

Hard coal, or anthracite. In the formation of *anthracite,* there is little doubt of its vegetable origin, but it seems to have been subjected to so high a temperature and pressure that practically all traces of its vegetable origin have been obscured. Hard coal contains less volatile matter than soft coal, and a higher per cent of carbon. Its per cent of ash is likely to be rather high. The state of Pennsylvania has a near-monopoly on hard coal, or anthracite, although China is said to have extensive hard-coal deposits. There are also large deposits of anthracite in the Ural Mountains. Hard coal makes a satisfactory fuel, but the price is high, particularly for those localities which are rather remote from Pennsylvania.

Coke is a good fuel. We know that coke is left as a residue from the destructive distillation of soft coal. Some coke is obtained as a residue from the distillation of petroleum. Coke burns with a clean flame, and it has a high heat content. Petroleum coke is a very satisfactory fuel, but the demand usually exceeds the supply.

DEMONSTRATION. Exhibit samples of coal, coke, and wood. Compare their physical properties. Try burning each.

3. GASES

Why are gases convenient fuels? It is difficult to conceive of a more convenient fuel than one which can be piped directly to the place where it is to be used; a fuel which can be turned on or shut off at a moment's notice; a fuel which can be kindled instantly; a fuel which leaves no solid ash; and a fuel whose heat can be concentrated exactly where it is wanted. Because gas is such a fuel, it seems too bad that it costs us more than some other fuels.

What is the cost to the consumer? The tabular form given below enables a consumer to get an idea of the relative prewar costs of different kinds of fuel:

FUEL	UNIT	COST PER UNIT	B.T.U.'S PER UNIT	NO. OF B.T.U.'S THAT CAN BE BOUGHT FOR $1.00
Gas	1000 cu. ft.	$ 1.00	530,000	530,000
Coal	2000 lb.	$12.00	25,000,000	2,083,333
Oil	gallon	7¢	136,000	1,942,857

From the table, it appears that there is little to choose between oil and coal, so far as cost is concerned. Gas, however, appears to cost more than three times as much as either coal or oil. Such a comparison, however, is not entirely fair, because gas companies usually make a price of from 50¢ to 60¢ per 1000 cu. ft. when gas is to be used for general house heating. One gets greater efficiency with gas, too, because combustion is likely to be more complete than with oil, and much more complete than with coal.

What is natural gas? When vegetable matter decomposes under water, marsh gas, or *methane*, CH_4, is formed. This gas may form as much as 90% of the natural gases that are found in quantity in West Virginia, Oklahoma, Pennsylvania, Texas, California, Kansas, Indiana, Louisiana, and some other states. It may occur with petroleum, or in localities remote from petroleum wells. When found in coal mines, it is known as *firedamp*. Natural gas has a high heat content, and it makes a valuable fuel.

How is coal gas made? In the manufacture of coke, coal gas is a valuable by-product. Sometimes coal gas is the chief product of manufacture, and coke is the by-product. (See Fig. 13–19.) In the commercial manufacture of coal gas, special grades of soft coal are heated in iron retorts until all the volatile matter is driven off. Such volatile matter contains ammonia and coal tar as impurities. From the retorts, the gas passes through a hydraulic main to the condensers, where it is cooled and the bulk of the tar and ammonia is removed.

In the *scrubbers* we find in use the *principle of countercurrents*, which is much used in industrial practice. The gas flows *upward* through a cylindrical tower, and water is sprayed *downward*. The tower is filled with inert rock to afford greater surface for the contact between the gas and the liquid, and to retard the speed at which the water falls. In some cases, rotary scrubbers are used to wash the gas by the use of moving paddles. In the scrubbers, tar is removed mechanically, and the last traces of ammonia dissolved.

In the *purifiers*, either lime or iron oxide is used to remove such impurities as carbon dioxide, sulfur compounds such as hydrogen sulfide, and cyanogen. The purified gas is then stored.

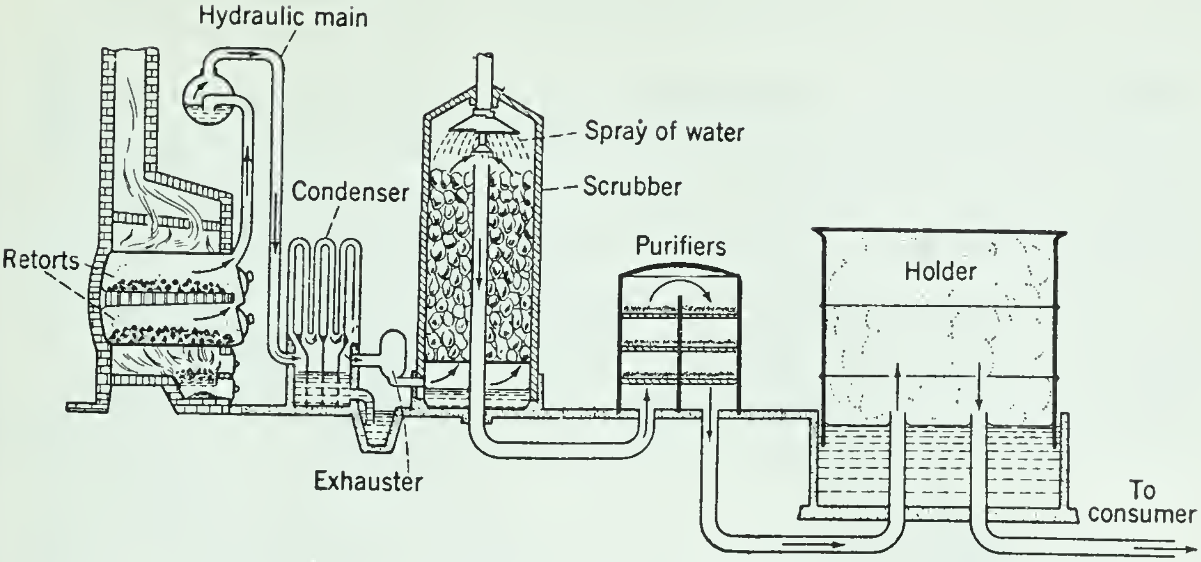
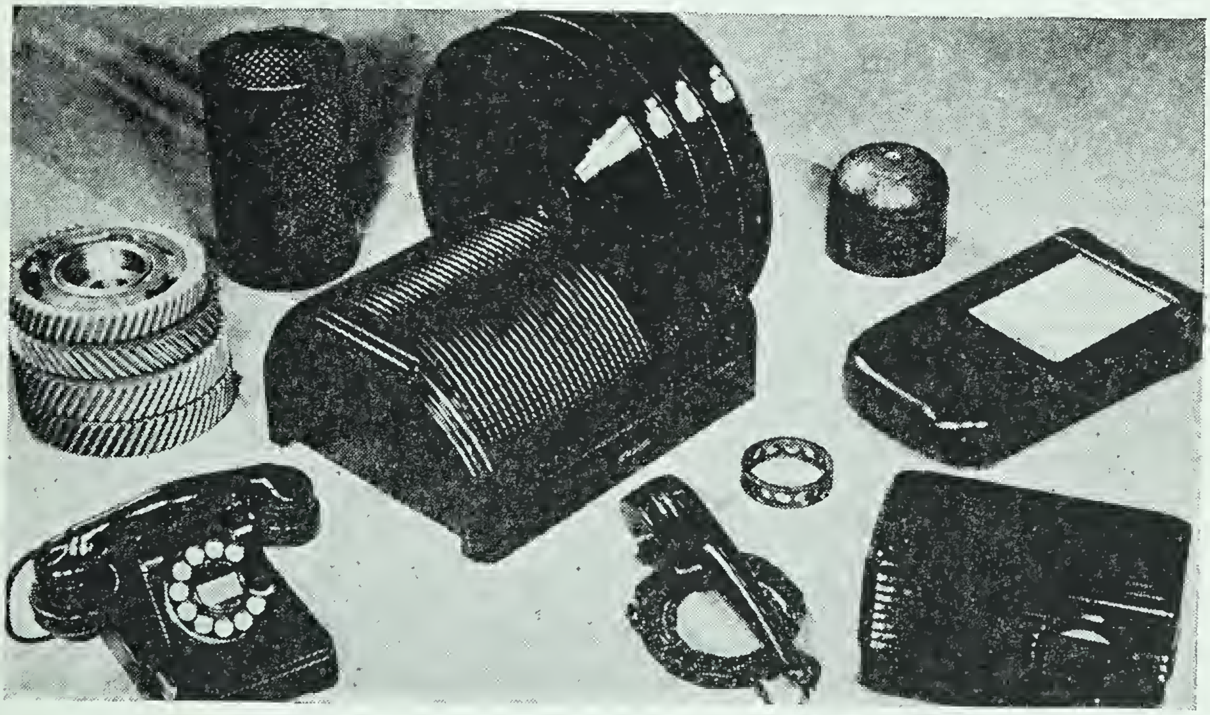


FIG. 13–19. In the making of coal gas, soft coal is heated in retorts without access to air. The gas which is driven off is cooled and washed in the condensers. Then it is pumped to the scrubbers where it is washed more thoroughly. Certain impurities are removed as it passes through the purifiers, which contain trays of lime or iron oxide. Then it passes on to the holder. In some plants, paddles rotating in water are used as scrubbers.



Courtesy Koppers Co.

FIG. 13–20. From soft coal and from coal tar the chemist extracts materials from which he makes many useful products. He spends long hours in research work, because such products do not come rolling forth when he waves a magic wand or plays the part of the "Pied Piper."

Why do we save by-products? From a ton of good gas coal it is possible to obtain from 10,000 to 12,000 cu. ft. of gas; from 1200 to 1400 lb. of coke; 120 lb. of coal tar; and about 20 gallons of ammoniacal liquor. Some of the many products that are made from the odorous, black coal tar, which at one time was carted away and dumped as waste, are shown in Figure 13–20.

What is producer gas? A cheap gas suitable for industrial use can be made by forcing a blast of hot air through a deep bed of coal or coke. (See Fig. 13–21.) In some cases a little steam is introduced. The flammable gas is carbon monoxide, which burns with a fairly hot flame, although producer gas may contain as much as 60% of nitrogen. This gas is used in making glass, steel, and pottery, although in some cases it has now been supplanted by fuel oils.

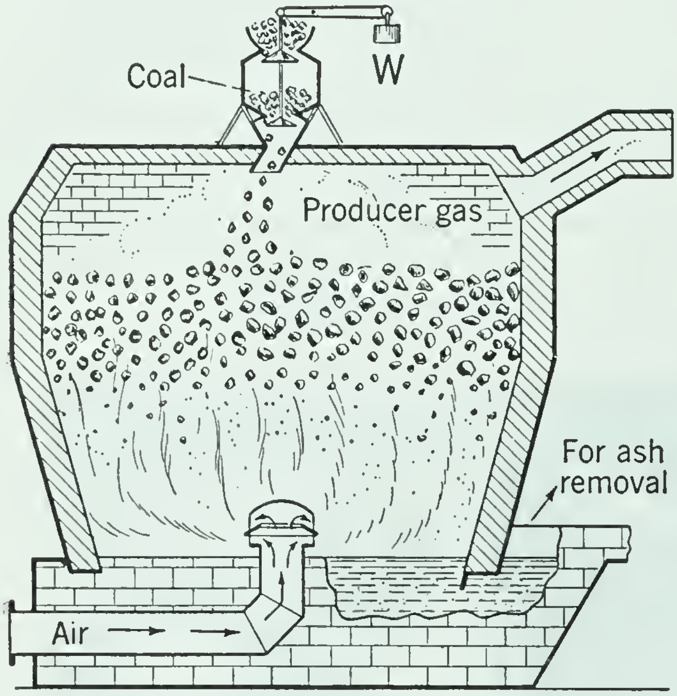


Fig. 13–21. In such a producer, gas for industrial uses is made by forcing hot air up through a bed of hot coal.

How is water gas made? The generating tower is filled with coke or hard coal, and a blast of hot air is forced up through it until the charge is heated white-hot. This takes only a few minutes. Up to this point, the process is the same as that for making producer gas. Then the air blast is stopped, and steam is forced up through the white-hot coal or coke. The following equation shows what reaction takes place:

$$C + H_2O \rightarrow CO \uparrow + H_2 \uparrow$$

Two combustible gases are thus formed. But the reaction is endothermic and the coke soon cools. For that reason, blasts of air and steam are used alternately.

How is water gas enriched, or carbureted? Since both hydrogen and carbon monoxide burn with flames that are so nearly colorless, water gas has no value for *illuminating* purposes unless it is enriched. At the present time, not much gas is used for lighting, and the water gas must be enriched to increase its fuel value. In the automobile carburetor, the water gas from the generator meets a spray of oils which can be converted into gases which burn with a yellow flame.

In the *superheater*, these oils are so strongly heated by passing through a checkerwork of hot brick or rock that their molecules are *cracked* into simpler molecules. For example, a hydrocarbon having the formula C_9H_{20} is a liquid which boils at about 150° C. If it can be cracked, or split up into hydrocarbons having such formulas as C_3H_8 or C_4H_{10}, then it will remain gaseous when cooled. The cracking process is also used to increase the yield of gasoline in the refining of petroleum. (See page 383.) In the enriching of water gas, the hydrocarbons are blended with the hydrogen and carbon monoxide to make a fuel gas or an illuminating gas which will not liquefy in the gas holder. Lime purifiers are used to purify the carbureted water gas.

Since nearly 40% of water gas is carbon monoxide, it is slightly more poisonous than coal gas. Even coal gas contains some carbon monoxide, and all fuel gases are suffocating and poisonous.

Some things chemists do with water gas. Water gas provides one of the cheapest sources of hydrogen. It is possible to cool water gas until the carbon monoxide liquefies, and then separate the gaseous hydrogen from it. It is possible to oxidize the carbon monoxide with steam in the presence of an oxide of nickel or iron as a catalyst, and then liquefy the carbon dioxide and separate the hydrogen from it. Since both hydrogen and carbon monoxide are used in making methanol, water gas is one of the sources of the raw materials used in this industry.

Oxyhydrogen flame. The oxyhydrogen blowpipe was invented in 1801 by Robert Hare, an American chemist. Essentially, this blowpipe consists of two concentric tubes. Hydrogen from a storage cylinder passes through the outer tube and is lighted at the tip of the blowpipe. The oxygen from a second storage cylinder passes through the inner tube, unites chemically with the hydrogen and produces a very hot flame. (See Fig. 13–22.) Hare succeeded in melting platinum, sand, aluminum oxide, and several other *refractory* substances. He modestly remarked, "Had I sufficient confidence in my own judgment, I should declare that gold, silver, and platinum were thrown into a state of *ebullition* by exposure on carbon to the gaseous flame." The oxyhydrogen flame, which gives a temperature of about 2300° C., is still used in melting platinum and quartz, and in the *fusion* of aluminum oxide in making artificial rubies.

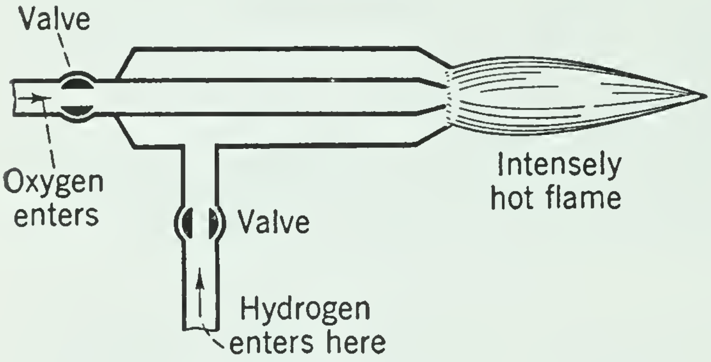


FIG. 13–22. The oxyhydrogen blowpipe was invented by Robert Hare.

Drummond produced the *limelight* by directing the flame from an oxyhydrogen blowpipe against a stick of lime. The lime does not melt, but it is heated white-hot. Any substance thus heated until it *glows* is said to be *incandescent*. At one time the limelight was much used for stage illumination and for stereopticon work. In fact, that explains the origin of the expression "in the limelight."

How is acetylene prepared? It was about the year 1899 that Willson, an American chemist, was trying to prepare metallic calcium by reducing calcium carbonate, $CaCO_3$, with coke in an electric furnace. He did not get any calcium, and in disgust he dumped the grayish-black residue which he did get into a stream at the rear of his house near Spray, North Carolina.

The product proved to be calcium carbide, CaC_2, a compound that interacts with water to form a combustible gas known as acetylene, C_2H_2. The equation for the interaction of water and calcium carbide follows:

$$\mathbf{CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2 \uparrow}$$

What are the properties of acetylene? This hydrocarbon, which has a peculiar odor, is very rich in carbon and it burns with a smoky flame, unless a special burner is provided. (See Figure 13–23.) With such a burner, *acetylene* burns with a fine, white light. At one time acetylene was used for automobile and bicycle headlights, and to light buildings in rural sections where other gas was not available. The powdered carbide may be dropped into water just fast enough to provide a steady evolution of acetylene gas.

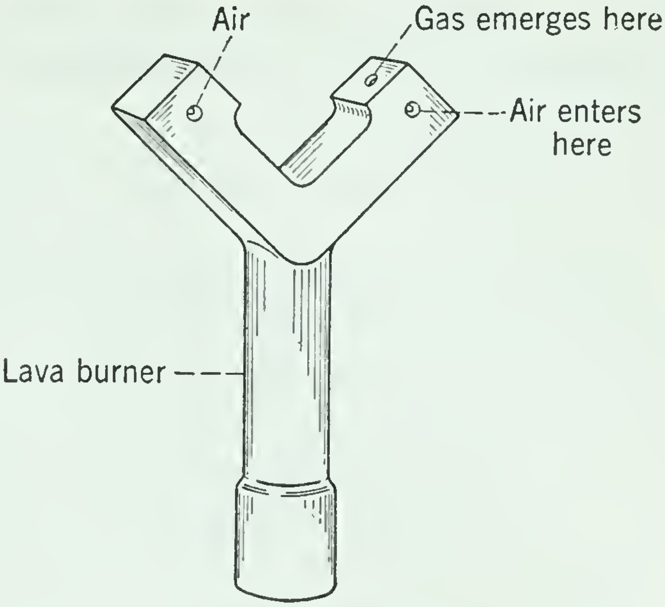


FIG. 13–23. A lava burner is used in burning acetylene.

In the making of acetylene, heat is absorbed. The endothermic reaction may be represented by the following thermal equation:

$$2C + H_2 + 58{,}100 \text{ calories} \rightarrow C_2H_2 \uparrow$$

When two moles of acetylene are burned, we get all the heat that would be formed by burning an equal weight (48 gm.) of free carbon, plus all the heat that would be formed

G. A. Douglas from Gendreau

FIG. 13–24. The oxyacetylene blowpipe is much used for cutting or welding metals. Sometimes the weld is made in place, without removing the broken parts.

by burning an equal weight (4 gm.) of hydrogen, plus all the heat that was absorbed in the making of the acetylene. The thermal equation follows:

$$2C_2H_2 + 5O_2 \rightarrow 4CO_2 \uparrow + 2H_2O + 641{,}000 \text{ calories}$$

With the exception of the atomic hydrogen flame, no flame is so hot as the *oxyacetylene* flame. The temperature is estimated at from 3000° C. to as high as 3700° C. Such a flame may be used for the cutting of iron and steel, or for welding iron as shown in Figure 13–24. The tip of the acetylene cutting flame is so hot that it will cut, melt, and burn its way through sheets of steel many inches thick.

For many purposes the oxyacetylene blowpipe has been substituted for the oxyhydrogen blowpipe. As indicated in Figure 13–25 acetylene is used instead of hydrogen as the flammable gas. The flame from the oxyacetylene blowpipe has a very high temperature, estimated at from 3400° C. to 3700° C. It is used extensively to cut through steel rails, to cut apart automobiles locked together in a crash, and to cut iron or steel in wrecking buildings. It has even been used underwater for cutting holes in the steel sides of wrecked vessels. A blowpipe similar to that shown in the figure is used for welding metals.

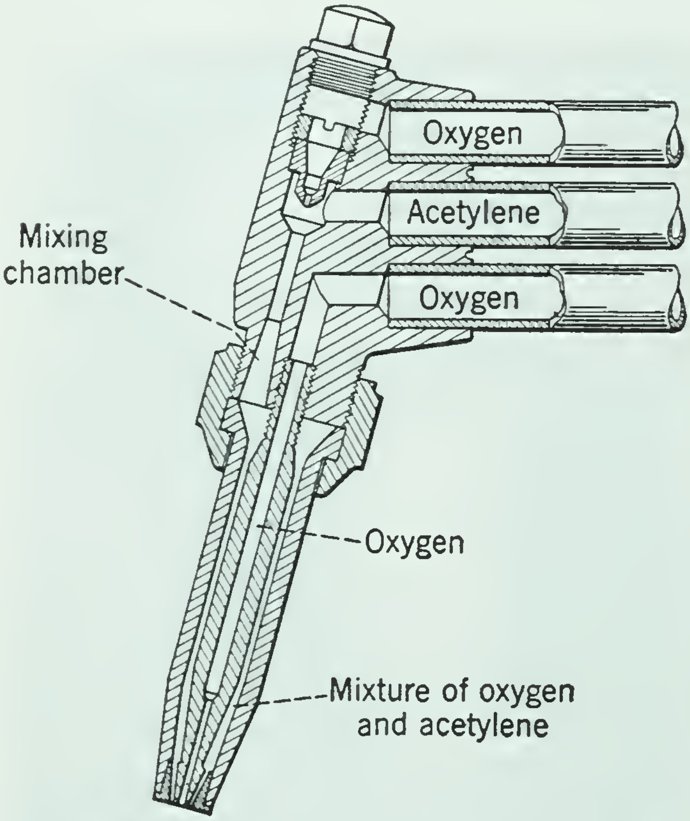


Fig. 13–25. The oxyacetylene blowpipe has many uses.

How did chemists solve the problem of storing acetylene? In the storing and marketing of most gases, they are compressed in strong metal cylinders. Such a method does not work with acetylene, because heat is absorbed during the making of the gas, and acetylene may explode even without the presence of air or oxygen. Many dangerous explosions occurred when attempts were made to compress it into cylinders for shipment. So low a pressure as two atmospheres may cause an explosion.

Then the *prest-o-lite* container, in which acetylene may be safely stored, was developed just about the time that some persons were ready to discard acetylene gas as a commercial product. Prest-o-lite containers are filled with asbestos saturated with acetone, $(CH_3)_2CO$, in which the acetylene is dissolved under pressure. It escapes when the valve is opened to release the stored gas.

Science marches on. Sometimes it is interesting to pause in our study of science and take a backward look. Only a few years ago our street and highway intersections were filled with thousands of "silent policemen," or "dummy cops," as they were commonly called. Such beacons contained cylinders of acetylene which flashed at intervals to warn motorists of blind roads and dangerous curves and crossings. Nearly all of them have disappeared.

But acetylene beacons which flash intermittently are still used in a large per cent of the lighthouses. At one time such flash beacons used Welsbach mantles which gave a very bright light when heated to incandescence. Such mantles, which were made of the oxides of cerium and thorium, were extensively used in gas lighting. But mantles now seem to be either obsolete or obsolescent. Burners made from lava are now used in lighthouses.

Dalén, a Swedish inventor, was awarded the Nobel prize in physics in 1912 for his work as inventor of the regulating devices which make the flashing of acetylene beacons automatic. Lighthouses in the Arctic regions operate without attention for as long a period as two years. Dalén invented a sun valve which shuts off the gas automatically when the sun is shining, but it turns it on again when it becomes dark, or when the sun disappears behind a cloud.

At about the time that Dalén completed his inventions, an explosion cost him his eyesight. This furnishes us with a tragic example of one man who gave his own eyesight in order that others might see, and avoid shipwreck.

Why do gases explode? Such gases as hydrogen, water gas, coal gas, or acetylene explode violently when they are mixed with oxygen and ignited, or heated to their kindling temperature. The combustion is almost instantaneous, and takes place throughout the entire mass. They form large volumes of gaseous material as they explode, and the heat of their combustion causes such gases to expand greatly. Such expansion during the explosion causes very great force.

Gasoline, ether, and alcohol, in the liquid state, do not explode. Neither does pure gasoline vapor explode. If, however, gasoline vapor is mixed with the right amount of air, it forms an explosive mixture which is many times as powerful as the same weight of dynamite.

What is meant by the explosive range of a gas? Fortunately, not all proportions of gasoline vapor and air explode. We have seen on page 377 the importance of proper mixtures. A mixture that contains too much gasoline vapor is too *rich* to explode. We have an example of this fact when the carburetor and cylinders of a gas engine are "flooded." Too *thin* a mixture does not explode either, and for that reason the choke is used to enrich the mixture by cutting off some of the air supply when we wish to start an engine in cold weather. The gasoline in such a case does not evaporate rapidly enough, and the mixture is too *lean.*

Any mixture of acetylene and air which contains anywhere from 3% to 30% of acetylene will explode. *Such a variation in percentage is called the explosive range of acetylene.* Any mixture of acetylene and air which contains less than 3% of acetylene does not ignite at all. Any mixture containing from 3% to 30% burns explosively. Any mixture containing more than 30% of acetylene burns quietly. As one might judge from the equation on page 398, the most violent explosion occurs when *two volumes* of acetylene are mixed with *five volumes* of oxygen, or *twenty-five volumes* of air.

Hydrogen has a wide explosive range. Any mixture of hydrogen and air which contains from 10% to 66% of hydrogen will explode.

The explosion is most violent when the mixture contains about 29% of hydrogen. The following table shows the composition of some fuel gases:

ANALYSIS OF GASES

	Coal Gas	Water Gas (Enriched)	Water Gas	Oil Gas
Candle power	17.5	25		65
Illuminants	5	16.6		45
Marsh gas	34.5	19.8	1.0	38.8
Hydrogen	49	32.1	52	14.6 Ethane
Carbon monoxide	7.2	26.1	38	
Nitrogen and carbon dioxide	4.3	5.4	9.0	1.1

SUMMARY

1. All matter is made up of *elements*, *mixtures*, and *compounds*. Both elements and compounds are called substances.

2. In elementary work we may define an element as the limit of chemical analysis. The element is the chemist's unit of matter. Ninety-two elements are known, and it is believed that all elements have been discovered. Only about thirty elements are well known except to chemists, and eight elements form about 98% of the earth's crust. Oxygen is the most abundant element known, and silicon ranks next in abundance.

3. Elements are classed as *metals* and *nonmetals*.

4. Any material made up of two or more elements is either a *mixture* or a *compound*. If the elements are chemically combined, and their proportion is a definite one, the substance is a *compound*. In a *mixture* the ingredients may be present in any proportion. *Every compound has a definite composition by weight.*

5. Oxygen, the most abundant element known, is found in the air, in water, and in many rocks of the earth's crust.

6. A substance that combines with oxygen to furnish heat energy is a *fuel*. All fuels contain carbon and hydrogen, and many of them contain oxygen.

7. Oxygen is a colorless, odorless, tasteless gas, which is slightly denser than air and slightly soluble in water. Oxygen is one of the most active elements known, especially at high temperatures.

8. That process by which oxygen unites with some other substance is called *oxidation.* The product formed as the result of oxidation is called an *oxide.*

9. *Ordinary combustion is rapid oxidation, during which light and noticeable heat are set free.*

10. Three things are needed before combustion can occur: (1) *combustible material;* (2) *a supply of oxygen;* (3) *enough heat to warm the material to its kindling temperature.* A fire may be extinguished by eliminating any one of the three essential factors.

11. The products of ordinary combustion are *water* and *carbon dioxide.* If the combustion of carbon is incomplete, *carbon monoxide* may be formed. Substances increase in weight when they burn, because the oxygen which is added to them has weight.

12. A good fuel should yield little ash; it should be inexpensive; it should not produce undesirable waste products as it burns; and it should have a high heat content.

13. One type of explosion is practically instantaneous combustion throughout the entire mass. Loose powder or a vaporized substance may explode since oxygen can mix with it readily.

14. The rapid expansion of exploding gases in an internal combustion engine drives the engine, which in turn drives the automobile.

15. The ideal mixture for a gasoline engine is 15 volumes of oxygen to 1 volume of gasoline vapor.

16. Gasoline is an organic substance obtained from the fractional distillation of petroleum. Other products thus obtained are petroleum ether, naphtha, benzine, kerosene, gas oils, lubricating oils, fuel oils, petroleum jelly, paraffin, and coke.

17. An ideal motor fuel should be sufficiently volatile to insure easy starting but not so volatile as to form bubbles of vapor in the fuel system. It should be economical, free from impurities, and of high octane rating.

18. The *liquid fuels* are of plant origin. They include the

alcohols, gasoline, benzol, kerosene, and fuel oils.

19. The *solid fuels* include: wood, peat, lignite, soft coal, hard coal, and coke. All are obtained from plants, either those of the present, or fossil remains of those living in past geologic ages.

20. Our most convenient fuels are the *gases*. *Natural gas* is found in many states. *Coal gas* is made by the destructive distillation of soft coal; ammonia, coal tar, and coke are valuable by-products. Water gas is made by forcing first a blast of hot air through a bed of coke or coal, and then a blast of steam. It is composed almost entirely of hydrogen and carbon monoxide, and it may be enriched by the addition of oils. Water gas is an important source of commercial hydrogen and of carbon monoxide, and it finds use in making *methanol* synthetically. Oxygen is used in both the oxyhydrogen blowpipe and the oxyacetylene blowpipe. *Acetylene* is made by adding water to calcium carbide. Its most important use is for the cutting and welding of metals.

How many of the following terms can you define or explain?

Element
Compound
Mixture
Metal
Nonmetal
Physical property
Chemical property
Physical change
Chemical change
Combustion
Oxidation
Kindling temperature
Flammable
Explosive mixtures
Petroleum
Refining process
Cracking process
Bergius process

SELF-TESTING EXERCISES

Answer These Questions

On a separate sheet of paper numbered from 1 to 8 write the letters for the phrases that answer the following questions correctly.

1. Which of the following terms or combination of terms correctly completes the statement? All matter is made up of (*a*) Compounds; (*b*) elements or compounds; (*c*) elements, compounds, and mixtures.

2. Which of the following terms correctly completes the following statement? The atom is the smallest particle which has all the characteristic properties of (*a*) An element; (*b*) a compound; (*c*) a mixture.

3. Which of the following statements is true about water? (*a*) It is an element; (*b*) it is a compound; (*c*) it is a mixture.

4. Which of the following processes is an example of chemical change? (*a*) Ice melting; (*b*) salt dissolving in water; (*c*) iron rusting; (*d*) water boiling.

5. Which of the following statements is true about oxygen? (*a*) It burns; (*b*) it is lighter than air; (*c*) it supports burning; (*d*) it is very soluble in water.

6. What is the correct name for a combustion reaction which takes place almost instantly? (*a*) Spontaneous combustion; (*b*) rapid oxidation; (*c*) an explosion.

7. What process increases the yield of gasoline from petroleum? (*a*) Bergius process; (*b*) cracking process; (*c*) destructive distillation process.

8. Which of the following is present in coal gas and causes it to be poisonous? (*a*) Carbon dioxide; (*b*) nitrogen; (*c*) carbon monoxide; (*d*) methane.

Complete These Statements

On a separate sheet of paper numbered from 1 to 14 write the words needed to fill correctly the blank spaces in the following sentences.

A total of . . (1) . . elements have been discovered. Any chemical action which occurs so rapidly that noticeable heat and light are produced is called . . (2) . . . Ordinary air is about . . (3) . . % oxygen by volume. Fuels may or may not contain oxygen, but they all contain . . (4) . . and . . (5) . . . The product formed by oxidation is called an . . (6) . . . Before a substance will burn it must be heated to its . . (7) . . . The law of indestructibility of matter states that no weight is ever . . (8) . . or . . (9) . . in a chemical reaction. Many products, such as gasoline, are obtained from petroleum by the process of . . (10) . . . Gasoline which has been made from natural gas is called . . (11) . . . Tetraethyl lead is added to gasoline to prevent . . (12) . . . . . (13) . . is a knockless motor fuel which is used as a standard in rating the antiknock properties of various grades of gasoline. The most convenient fuels are . . (14) . . .

Are These True or False?

On a separate sheet of paper numbered from 1 to 8 write a T *or an* F *to show whether each statement is true or false.*

1. Mixtures have no definite composition.
2. For most fuels the products of burning are carbon dioxide and water.
3. Spontaneous combustion usually takes place in the absence of air.
4. Ethylene bromide in gasoline prevents engine knocks.
5. A gasoline cannot have an octane rating of more than 100.

6. Coal gas is made from soft coal.
7. Natural gas is composed largely of methane.
8. Gasoline vapor has a wide explosive range.

QUESTIONS

1. What are the four most abundant elements?
2. Name five elements; six compounds; four mixtures.
3. Make a list of eight metals; make a list of eight nonmetals.
4. How can one separate the iron from a mixture of iron filings and sulfur?
5. Is it possible to separate the iron from the sulfur in the compound known as iron sulfide? If so, how? (Class discussion.)
6. Suppose you are given a mixture of sand and sugar. How would you proceed to separate the sand from the sugar?
7. What are some of the characteristic properties of gasoline? Of alcohol? Of gold? Of iron? Of copper? Of platinum?
8. How would you distinguish between gasoline and alcohol? How can one tell gold from copper? How can one distinguish salt from sugar?
9. Why is the law of definite proportions so important in chemistry?
10. Is it correct to say that the physical properties of a substance depend upon its behavior when it is alone, and its chemical properties upon its behavior or conduct with other substances?
11. How would you test a bottle of gas to learn whether it is filled with air or with oxygen? To distinguish between oxygen and carbon dioxide?
12. Paper, wood, and coal may be added successively when starting a hard coal fire. Explain.
13. Why does a book or a magazine burn slowly when closed, and so rapidly when opened?
14. Why is a candle flame extinguished by blowing? Why does blowing a larger fire make it burn more vigorously?
15. Why is a spark in a flour mill likely to cause an explosion?
16. What are some of the uses man makes of explosives?
17. Should you use water or sand to put out a gasoline fire? Explain.
18. Baking soda gives off carbon dioxide when it is heated. Do you think that baking soda would make a good fire extinguisher? Explain.
19. Pyrene fire extinguishers contain carbon tetrachloride, a *volatile* liquid which does not burn. Explain how it puts out a fire.
20. Carbon tetrachloride may be used to remove grease spots, chewing gum, and even lipstick. What advantage does it have over gasoline for such purposes?

21. Why is no solid ash formed when fuel gas burns?

22. Explain why water and carbon dioxide do not burn.

23. What would be the best thing for you to do if your clothing were to catch fire?

24. What kind of chemical would you add to paint to make it "dry" faster?

25. Why should wood and such metals as iron be kept well painted?

26. Why should oily wastes be kept in metal containers in shops and factories?

27. When testing oxygen gas, should the bottles be kept mouth upward or mouth downward? Give a good reason for your answer.

28. Discuss the value of wood as a fuel.

29. What are the advantages and the disadvantages in the use of hard coal as a fuel?

30. Give two important reasons why wood has a lower heat content than soft coal does.

31. How is petroleum refined?

32. Discuss four methods used to increase the yield of gasoline.

33. How can synthetic gasoline be obtained by the Bergius process?

34. Under what conditions does gasoline vapor explode?

35. What is the chief purpose of the carburetor of a car?

36. Why is tetraethyl lead, with ethylene bromide, sometimes added to gasoline?

37. Why is it dangerous to work in a closed garage when the engine of the car is running?

XIV

The Automobile Embodies Many Principles of Machines

A. FRAME—MOMENTS OF FORCE

The main frame which supports the entire weight of the car is really one large lever. If the center of gravity of the car were halfway between the front and rear axles, we could then say that the weight of the car is equally distributed between front and rear wheels. Regardless of the location of the center of gravity we can say that the upward moment produced by the front axle is equal to the upward moment produced by the rear axle (moments counterclockwise equal moments clockwise).

B. SPRINGS AND SHOCK ABSORBERS

1. THEY ABSORB THE INERTIA OF THE CAR

Elasticity, compression, and hydraulics. The properties of elasticity, compression, and hydraulics are put to practical application in the absorption of the inertia of a car.

When a wheel strikes a bump on the road surface it must be raised in rolling over the elevation. When the upward motion of the wheel is rapid the inertia of the car tends to prevent the body of the car from being lifted. This causes a load to be placed on the wheel far exceeding the load which is normally carried. The elasticity of a coil spring or an elliptical spring permits it, when placed between the wheel and the body of the car, to absorb the inertia of the car by allowing the wheel to go up and down without forcing the body of the car to do likewise. The tire absorbs some of the car's inertia in the elasticity of the compressed air with which it is inflated. We have already learned that the volume of a gas varies inversely as the pressure (Boyle's law). When a tire strikes a stone its volume becomes less (temporarily) because of the sudden increase in pressure caused by the stone.

2. SHOCK ABSORBERS OVERCOME OSCILLATIONS

Single- and double-action. Since it is practically impossible to construct a spring which will absorb all of the jolt before it reaches the occupants of the car, many types of shock absorbers are used to assist the springs. Shock absorbers also regulate the speed of the rebound of the main spring so that it returns to normal position slowly, thus eliminating sudden shock and overcoming the tendency of the car to oscillate. The principle commonly used is that of a piston forcing a liquid such as glycerin or oil through a small valve in the side of a cylinder into the opposite end of the same cylinder. A needle valve in the end of the piston allows the fluid to flow through it as it is forced back by the rebound of the main spring. A combination of two such cylinders operated by the shock absorber lever is called a double-action shock absorber. This principle in a single-action cylinder is sometimes used in the recoil mechanism of large guns.

3. KNEE-ACTION

No front axle. The property of elasticity is made use of in the tires, main springs, and shock absorbers. In order to further reduce vibration caused by uneven road surfaces, some car manufacturers use the coil type of spring in individual suspension of wheels. One type of independent suspension of front wheels is known as knee-action. This type of suspension eliminates the front axle. An axle tends to act as a second-class lever. The wheel which strikes a stone is the free or effort end of the lever. The other wheel acts as a fulcrum with the weight of the car located between the fulcrum and the effort. Lifting one end of the lever (the axle) lifts the weight of the car. By individual suspension the tendency to lift the car when one wheel strikes a bump is reduced.

C. FRICTION—SLIDING AND ROLLING FRICTION

1. ROLLER AND BALL BEARINGS

Bearings reduce friction. In Chapter III we learned that rolling friction is less than sliding friction. Where friction is undesirable in that it reduces the efficiency of a machine one method of reducing it is by means of ball bearings and roller bearings (Figs. 3–18, 3–19, and 3–21). Roller bearings are used when heavy loads must be supported. You will find them used as the main bearings in the front wheels of a car, as well as in the rear axle housing and in the differential and the drive shaft. Friction is reduced in other moving parts of the car, such as the steering mechanism and the motor, by roller bearings.

2. LUBRICATION

Lubrication reduces friction. Due to the sudden pressures exerted on the bearings of the crankshaft by the power strokes of the pistons, the connecting rod bearings and the main bearings of the crankshaft are plain rather than roller. Two metallic surfaces moving over each other, as in a plain bearing, cause high resistance or friction which may result in excessive wear and high temperature. A layer of lubricating oil placed between two metallic surfaces greatly reduces friction and wear. Plain bearings require much more lubrication than do roller and ball bearings since plain bearings are a friction type of bearing. Gasoline engine lubrication is complicated by the fact that engines run at high temperatures, which have a tendency to thin out the lubricating oil. Lubricating the bearings of an engine is accomplished by two general methods, the splash and the pressure systems. Practically all of the larger and more complex gasoline engines use the pressure system which makes use of an oil pump. In simple motors the splashing of the cranks of the crankshaft in the oil in the bottom of the crankcase oils the main bearings of the motor. (See Fig. 14–1.)

The transmission and differential use heavier grades of oil or grease than are used by the engine. The same is true of spring-hanger bearings, water-pump bearings, and the fan bearing.

3. TIRES

Useful friction. The force of friction between the tires and the road must be greater than the force necessary to start the car. The purpose of the tread on the tire is to increase friction or traction, so that the wheels do not "spin" in starting and in going up a steep hill.

4. BRAKES

Another example of useful friction. In the automobile inertia has its advantages and disadvantages. The flywheel on the crankshaft of the motor makes use of inertia to keep the engine running smoothly. In starting, the motor has to do extra work in order to overcome the inertia due to the weight of the car. The brakes, in stopping the car, have to overcome inertia due to the car's momentum. By means of friction the brake accomplishes this by changing kinetic energy into heat energy. The latter is lost by radiation. In downhill driving the work of the brakes can be reduced by shifting to intermediate or low speed, thus putting the inertia of the motor to practical use.

The overcoming of inertia or momentum must be equally distributed to all four wheels; otherwise the car will tend to swerve, skid, or overturn. By means of hydraulic brakes, which we have already discussed, the equalization is assured. In some cars the braking force on the front wheels is slightly greater than on the rear wheels. This is accomplished by making the piston diameter in the front brakes slightly larger than that of the rear brake piston.

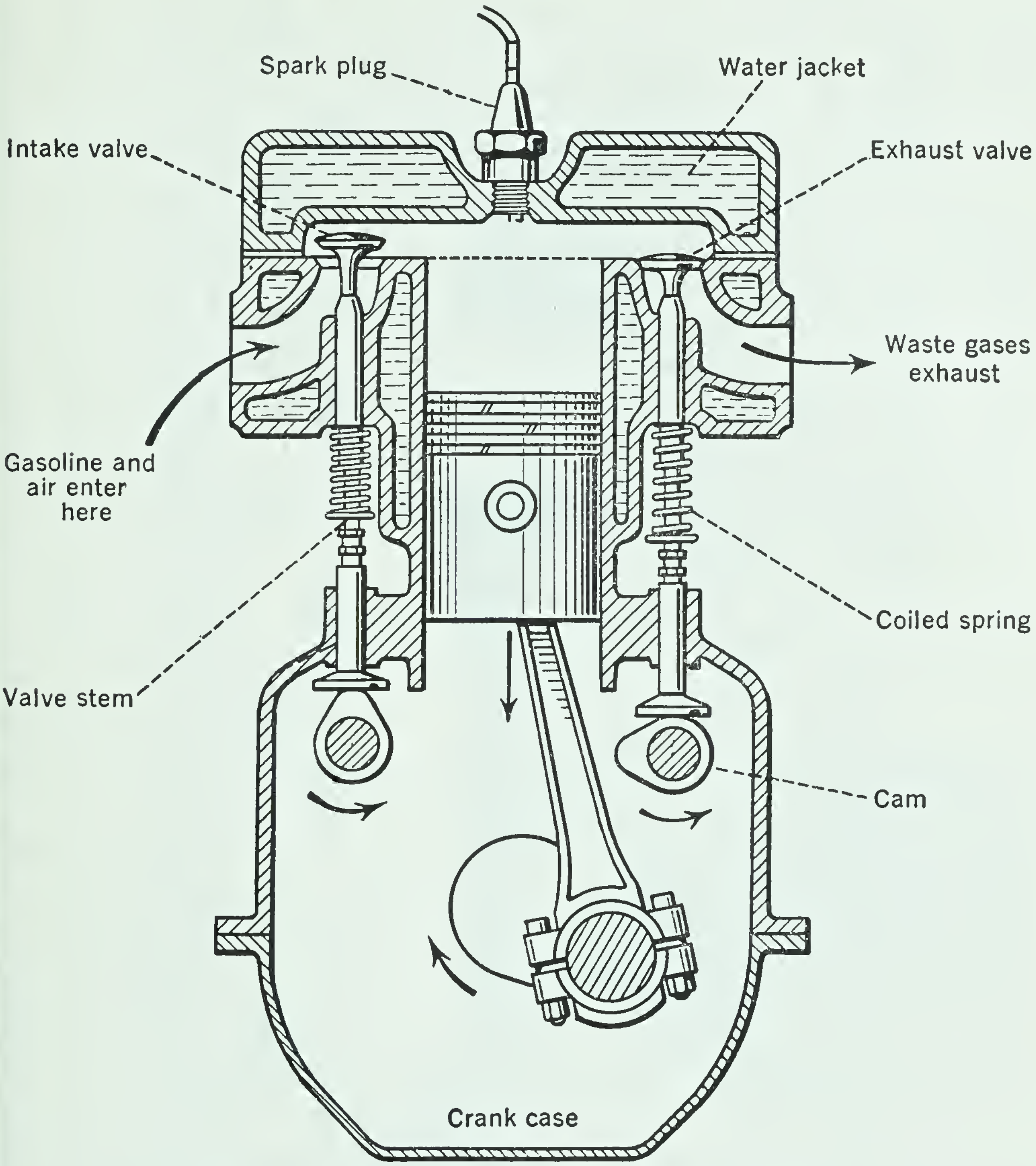


Fig. 14–1. Sectional view of a gasoline engine.

5. CLUTCH

What is the plan of the drive mechanism? If one were to saw a car through the center from front to back, its profile would be found to resemble Figure 14–2. In the extreme front we have the radiator, with the fan as a part of the cooling system immediately behind it. Then we have the engine, mounted on rubber pads and

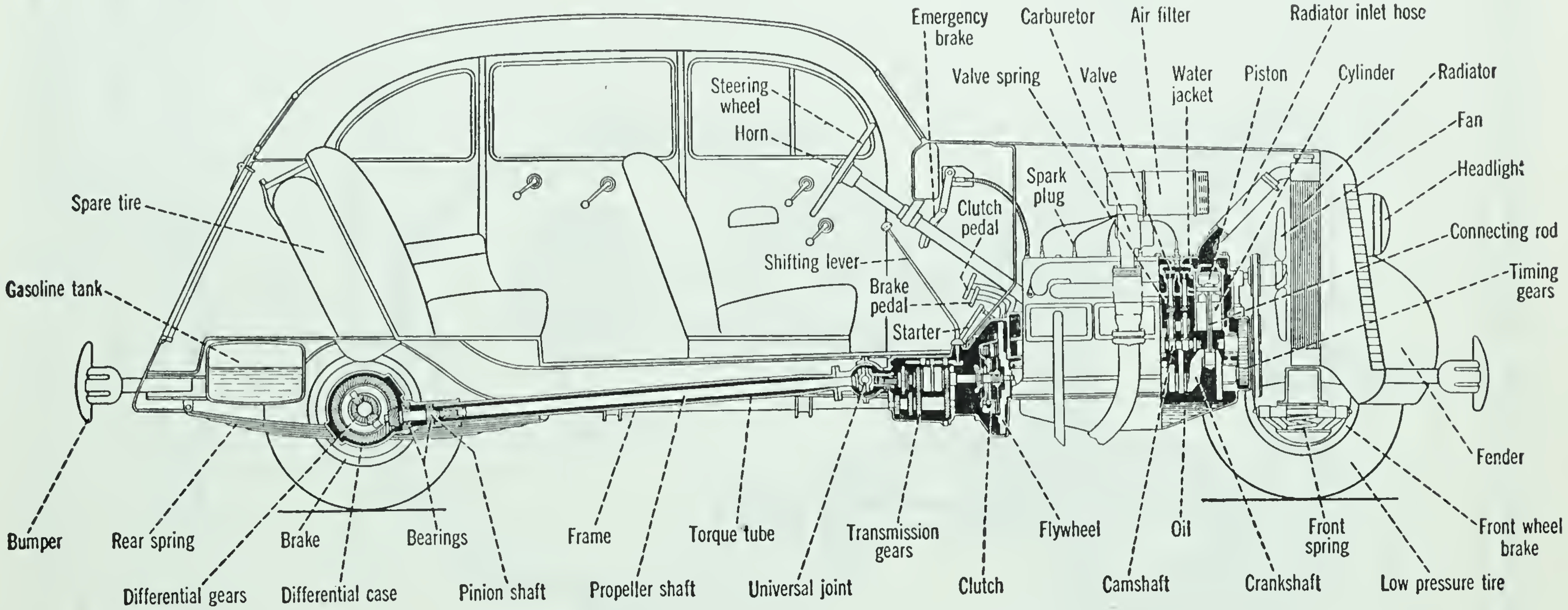
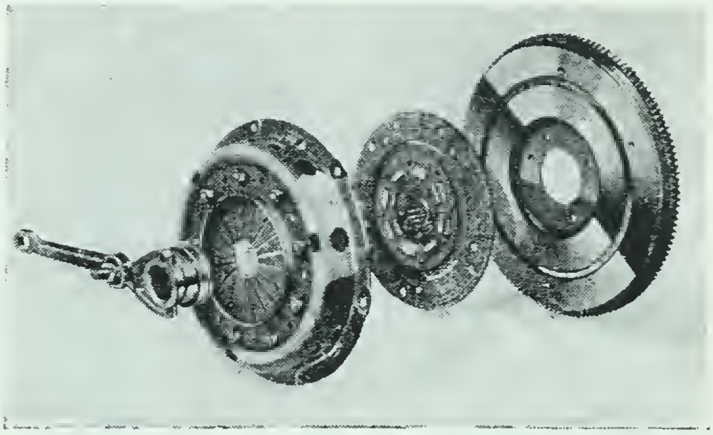


Fig. 14–2. The way an automobile would appear after being sawed lengthwise is seen in profile. It shows the position of the radiator, the fan, the engine, the crankshaft, the flywheel, the clutch, the transmission gears, the universal joints, the propeller shaft, the differential, and many other parts.

fastened securely to the frame. Beneath the engine is the crankshaft, and fastened to the engine is the carburetor. At the rear end of the crankshaft, which is mounted in several bearings to reduce vibration, we find the flywheel. A clutch is used to connect the crankshaft with the driven part of the car.

The clutch is connected to the transmission gears, which are used to vary the speed. A propeller shaft is used to connect the transmission gears with the differential in the rear axle. There are two universal joints in the propeller shaft to permit it to bend up and down, or from side to side. They are similar to the joints in our wrists, which permit freedom of motion in any direction. When the differential, which is mounted in the center of a divided rear axle turns, it causes the rear wheels to turn, too, and drive the car.

How does the clutch work? The gas engine does not start under load. Hence it must be disconnected from the rest of the car while it is coming up to speed. The following is the problem that engineers had to solve: Given a crankshaft spinning several hundred revolutions per minute; also a drive shaft which is stationary. The two must be connected so that they will both revolve at the same speed, with as smooth an engagement of the two parts as possible. The answer to the problem is the *clutch*. (See Fig. 14–3.)

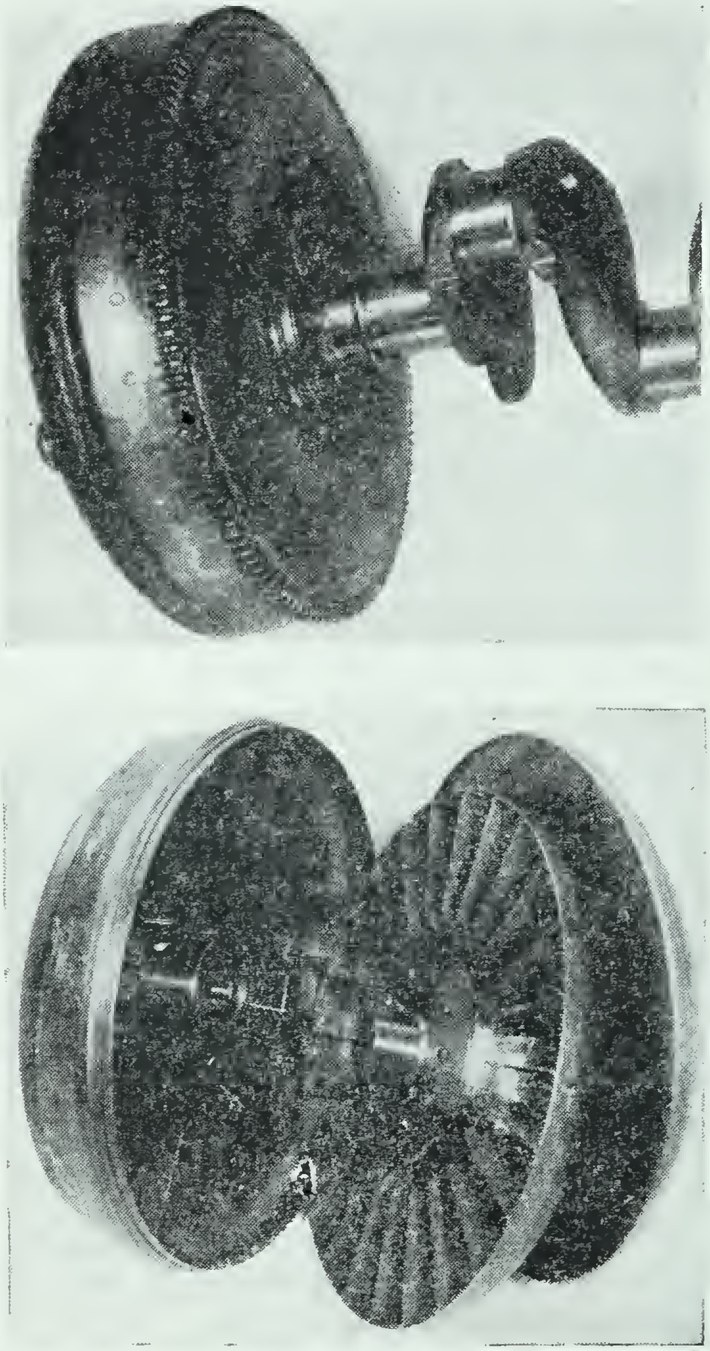


Courtesy of Chevrolet Motors Sales Corporation

Fig. 14–3. The clutch is used to connect the engine with the propeller shaft through the transmission gears.

Attached to the stationary shaft is a plate, or a series of plates, covered with a ring of "friction" material. This ring of friction material can be pressed up against the face of the flywheel by means of strong springs. A lever, operated by the left foot of the driver, can be used to *engage*, or to *disengage*, the clutch.

When the left foot is pressed down against the clutch pedal, it pushes the clutch plate backward, and disconnects the crankshaft from the drive shaft. Then the engine "idles" or runs without driving the car. As the left foot is lifted from the clutch lever, the springs push the clutch plate forward to engage the clutch. The clutch should slip a little as it is engaged gently, and then hold firmly. A sudden engagement of the clutch results in a jerking motion.



Courtesy of the Chrysler Corporation

FIG. 14–4. The liquid clutch is now used by some busses and automobiles.

The clutch is used in starting the car, in stopping the car, and when shifting gears. Trying to beat the other fellow away in traffic puts undue strain upon the clutch. Some drivers get the habit of "riding the clutch" by keeping the left foot upon the clutch pedal all the time when driving. The habit is a bad one, as a little unconscious pressure on the clutch means that the clutch may slip, and the friction material used as a clutch facing soon wears away.

How does the liquid clutch work? By the use of the newer liquid clutch, the necessity of shifting gears is avoided, except in reverse. As used on busses, it is unnecessary for the driver to operate a clutch in the ordinary way or to use a gearshift lever unless he wishes to back up. There is no jerking or stalling of the engine when the car equipped with such a clutch starts, and the car can be stopped, too, without killing the engine, merely by the use of the brakes.

With such a *fluid drive*, as it is called by one company, the crankshaft has at its end a set of blades something like a water wheel. Facing this water wheel is a second set of blades, mounted on the end of the transmission shaft. Both sets of blades are enclosed in a sealed housing filled with oil. As the engine picks up speed, the blades attached to the crankshaft through the flywheel set the oil in motion, and the moving oil sets the blades attached to the transmission shaft in motion as it impinges upon them. Thus the power is transmitted to the rear wheels through the liquid clutch. (See Fig. 14–4.)

D. POWER PLANT—RATE OF DOING WORK

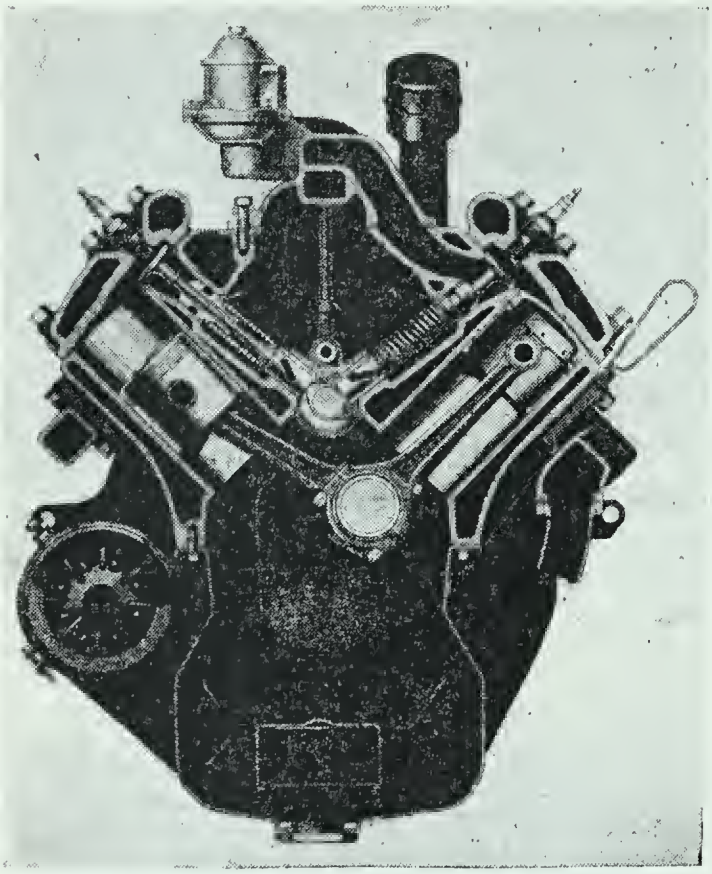
1. FOUR-CYCLE ENGINES

The automobile has three parts. For convenience, we may consider that the automobile consists of three parts: (*a*) *the power plant;* (*b*) *the chassis, or running gears;* (*c*) *the body.* In this section, we shall pay especial attention to the physical principles that are utilized by the power plant.

The power plant has been improved. We have already learned how a gasoline engine works. The first engine, invented by Lenoir, a Frenchman, was very wasteful because the gasoline vapor was not compressed before it was ignited. The compression stroke was added by Otto, a German, about eighteen years later. It cut the gasoline consumption to about one-third that of Lenoir's engine.

Since the automobile became practical, men have seen the gas engine grow from a single-cylinder power plant, which required a 300-lb. flywheel to keep it going between successive power strokes, to the two-cylinder engine, the four-cylinder, and finally to the straight eight or the V-eight which is now found in many engines. (See Fig. 14–5.) To secure very great flexibility, sixteen-cylinder engines are in use in some heavy cars.

In addition to increasing the number of cylinders in the power plant, the compression ratio has also been increased. This increases the efficiency of the engine. At one time a compression ratio of 4 to 1 or 5 to 1 was common. Now, the refining of gasoline to give it a high octane rating makes it possible to increase the compression ratio in some of the new engines to 7 to 1. For such engines, a gasoline having an octane number of 80 or more is desirable to prevent engine knocks.



Courtesy of the Ford Motor Company

Fig. 14–5. Cutaway view of an eight-cylindered automobile engine.

How does the gas engine work? The gas engine is an *internal combustion engine*. The carburetor vaporizes gasoline, benzol, or alcohol, and mixes the vapor with air to form the explosive mixture. Such an explosive mixture is ignited in the cylinder of the gas engine by means of an electric spark. The energy from successive explosions drives the piston and furnishes the power. The cylinder has thick walls, a piston which fits the cylinder so tightly that gas cannot pass, a connecting rod which connects the piston with the crankshaft, one valve to let in the explosive mixture, and another valve to let the waste gases escape. Let us see what happens in a single-cylinder *four-cycle*, or *four-stroke* engine during each stroke:

Stroke 1. To start the engine, we pull the piston down from a position near the top of the cylinder, either by means of a crank attached to the crankshaft or by means of an electric motor used as a self-starter. This produces a partial vacuum in the part of the cylinder above the piston. The explosive mixture from the carburetor is pushed into the cylinder through the valve V', Figure 14–6. The outlet valve is closed. This cycle or stroke is called the *intake*. It fills the cylinder with the explosive mixture.

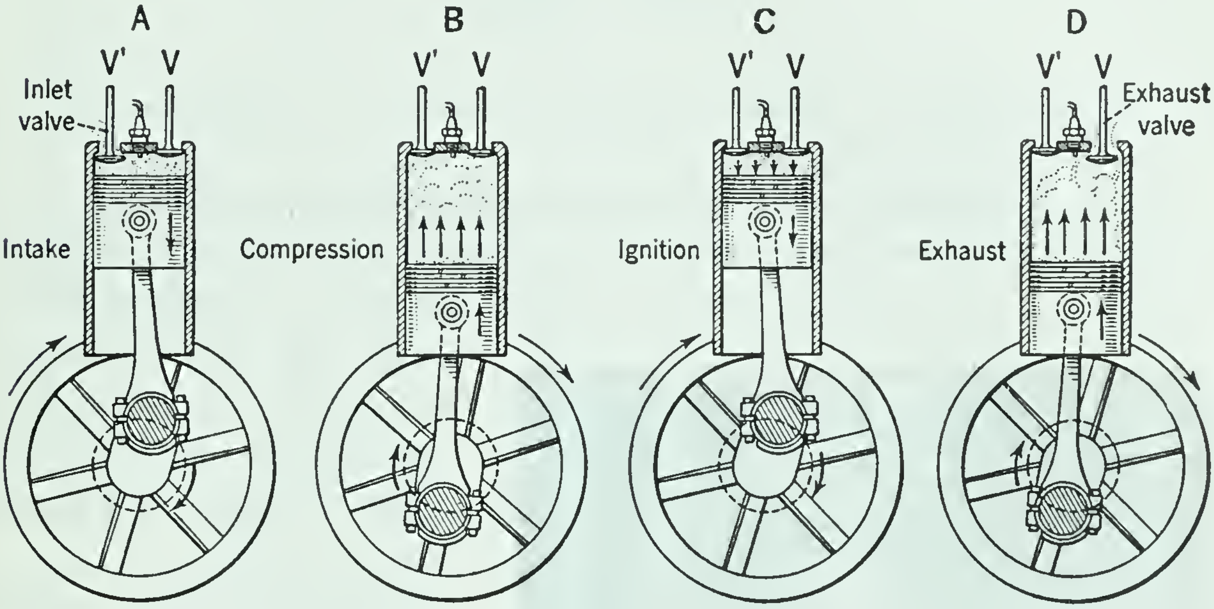


FIG. 14–6. The four-cycle gas engine. *A*. Intake. *B*. Compression. *C*. Ignition. *D*. Exhaust.

STROKE 2. As we continue to crank the car the piston moves upward. It takes more force now, because we are compressing the gas to about one fifth or one sixth of its former volume. During this *compression* cycle, or stroke, both valves must be closed, or we could not compress the gas.

STROKE 3. When the piston reaches the top, or nearly so, an electric spark is produced between the terminals of a spark plug set in the metal cylinder head. The spark ignites the mixture and starts the explosion. The hot gases expand and drive the piston downward with great force. This is the *working* cycle or stroke of the piston. Both valves must be closed during this *ignition* cycle, or power stroke.

STROKE 4. The upper part of the cylinder is now filled with waste gases left after the explosion. On the next upstroke of the piston these gases are pushed out of the cylinder through the exhaust valve, *V*, Figure 14–6 *D*. The *exhaust* cycle, or stroke, completes the operation, and the whole process starts anew. There are generally 1200 or more complete cycles per minute.

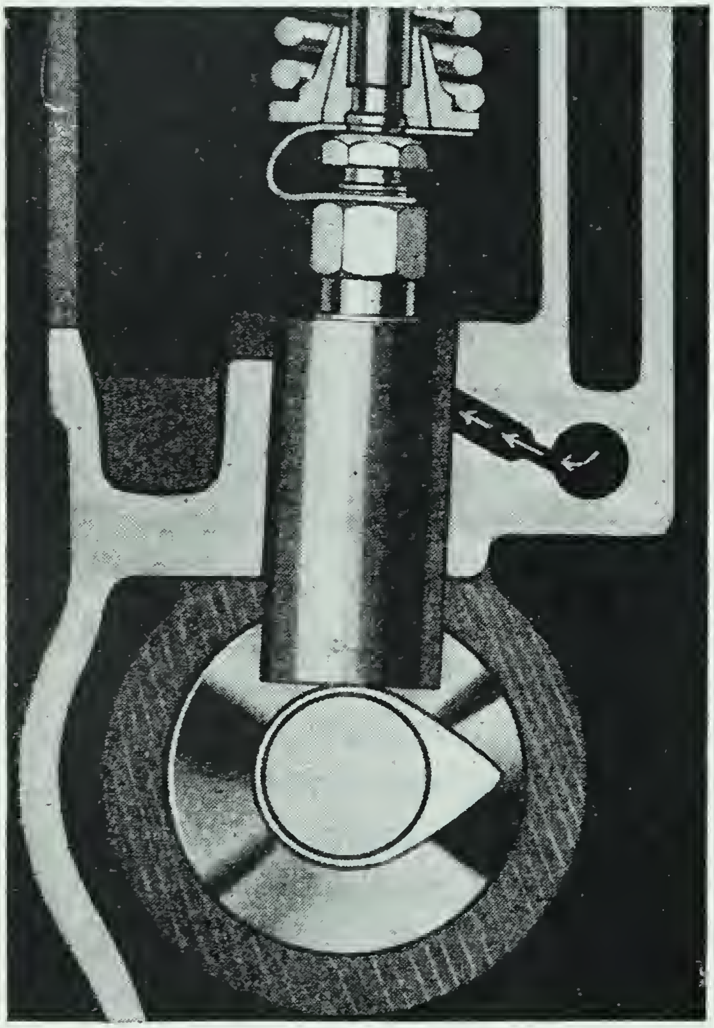
The Society of Automotive Engineers uses the following formula for finding the horsepower of a gas engine:

$$\text{H.P.} = \frac{D^2N}{2.5}$$

In the formula, D equals the diameter of the cylinder in inches and N the number of cylinders.

What keeps the engine going between power strokes? The single cylinder engine is working only one-fourth of the time. To keep the parts moving between power strokes, a flywheel with a heavy rim is attached to the end of the crankshaft. The inertia of this wheel keeps the engine running fairly steadily.

Multicylindered engines are used for automobiles. When there is only one cylinder, there is one power stroke for every 720° of crankshaft revolution. With two cylinders, there is one power stroke for every 360° of revolution. With a four-cylinder engine, there is a power stroke for every half-revolution of the crankshaft, and the eight-cylinder engine furnishes a power stroke for every 90° that the crank shaft revolves. The more cylinders there are, the



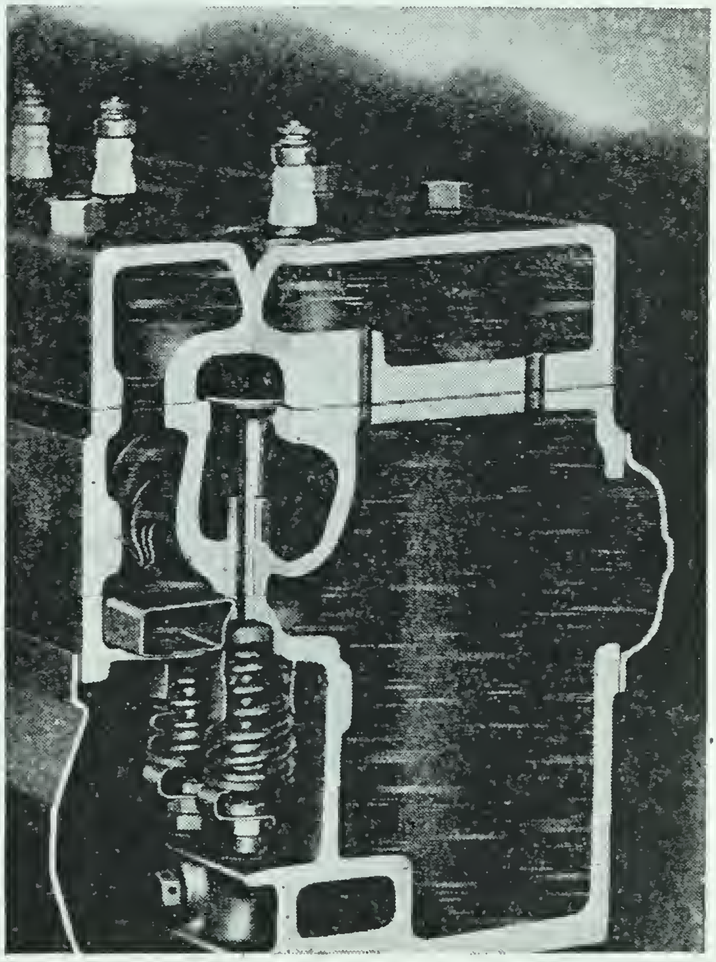
Courtesy of the Studebaker Corporation

FIG. 14–7. The projection on the cam lifts the valve stem as the shaft rotates.

greater the flexibility of the engine. The flywheel may be made smaller, too. An eight-cylinder engine may be throttled down to run more slowly in traffic with less danger of stalling than a four-cylinder engine.

How are the valves controlled? To control the valves, which must open and close at exactly the right time, cams are used. A camshaft is geared directly to the crankshaft, and turns with it. In Figure 14–7, one can see how the cam lifts the valve stem as the camshaft rotates. A spring closes the valve just as soon as the cam projection has passed the end of the valve stem.

Figure 14–1 shows a sectional view of one cylinder of a gas engine. The cams are shown, as well as the valve springs, and the manner in which the valves are seated. In actual practice, with an L-head motor, both valves are on the same side of the engine cylinder, in line with each other so that they can both be operated from the same camshaft. In some engines, the valves are in the cylinder head. They are operated by a camshaft, through a rocker-arm mechanism.



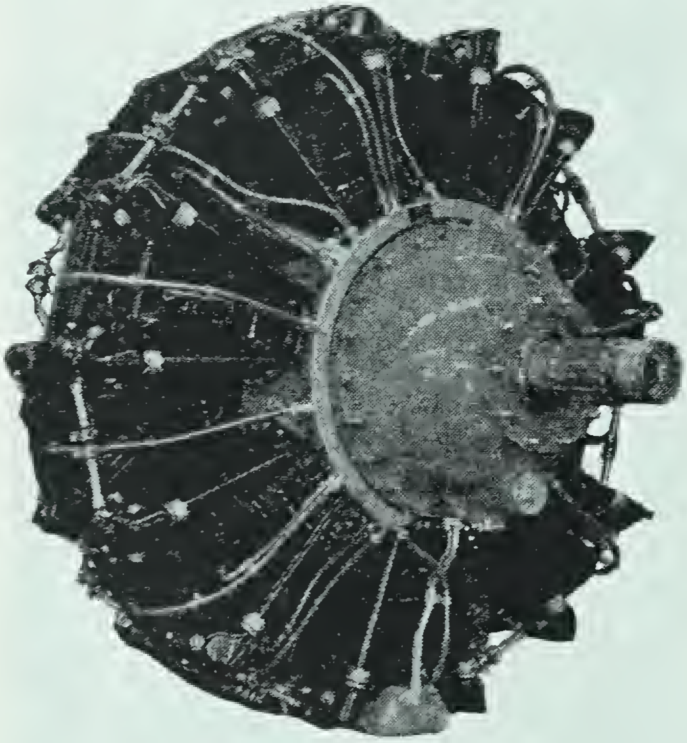
Courtesy of the Studebaker Corporation

FIG. 14–8. Water circulates around the cylinders and the cylinder head to cool them.

How is the engine cooled? The constant series of explosions in a gas engine soon heats the cylinder head, the piston, and the cylinder walls strongly. A gas engine does not work well until it is hot, but it must not get hot enough to "freeze" the piston or to warp or distort the walls or cylinder head unduly. Oil in the crankcase is splashed and pumped to all the moving parts to lubricate them and to help keep them cool.

In automobile engines the cylinder block is enclosed by a water jacket so that cold water can circulate around each cylinder. (See Fig. 14–8.) A centrifugal pump is used to keep the water circulating. As the water becomes warm from the heat it absorbs, it flows out the top of the engine to the top of the radiator. In the tubes of the radiator it is cooled by air which is constantly drawn through the radiator. A fan behind the radiator causes the draft. The water which has been cooled in the radiator then returns to the lower part of the engine to absorb more heat.

Motorcycle engines and airplane engines are generally air cooled. Flanges or fins attached to the outside cylinder walls absorb the heat and increase the surface exposed to the air so that the cooling will be more effective. (See Figs. 12–17 and 14–9.)



Courtesy of the United Aircraft Corporation

FIG. 14–9. Airplane engines are generally of the radial type. Twin ignition is in common use, and the engine is usually air-cooled.

What are the advantages and disadvantages of the gas engine? (1) *Advantages.* The gas engine has an efficiency of about 25%, considerably higher than that of the steam engine. It is very compact and furnishes a high horsepower for its size. The Wright Cyclone engine, of the type used by Howard Hughes in his around-the-world flight, develops 1 H.P. for little more than 1 lb. of weight. The fuel, too, takes up very little room. Without the development of the gas engine, the airplane would not be practicable. The gas engine may be

Official Photograph U. S. Army Air Forces

FIG. 14–10. Students learning about the operation of a V-type multi-cylinder engine.

started at a moment's notice, and it can be stopped almost instantly. It does not waste fuel when it is stopped. The steam engine cannot be started until the fuel has been burning long enough to produce steam, and the fuel continues to burn after the engine is shut down. There is no need for stoking a gas engine, but the steam engine must be stoked frequently unless equipped with an automatic stoker.

(2) *Disadvantages.* The gas engine is very sensitive. The spark must occur at the right time, and it must occur every time. The gas engine cannot be run economically at low speeds. It cannot be reversed. The fuel is expensive and it promises to be even more so. The speed of a steam engine can be easily regulated by a throttle which governs the amount of steam entering the cylinders. While the speed of a gas engine can be varied by controlling the gas supply, yet gears are necessary to secure the proper variation in speed. The gas engine will not start under load, and

a clutch mechanism is necessary to connect the engine with its load after the engine has been brought up to speed. The gas engine is rather noisy and the gases from the exhaust are disagreeable and poisonous to breathe.

Horsepower — B.H.P. and I.H.P. We have already learned that power is the rate of doing work and is measured in horsepower (H.P.). If a motor does 33,000 ft. lb. of work per minute it is working at the rate of one H.P.

Brake horsepower (B.H.P.) is a term used to indicate the power which is available at the drive shaft of the car or the propeller end of an aircraft engine. This power can be determined by measuring the amount of electrical energy generated when the motor is attached to a generator.

Indicated horsepower (I.H.P.) represents the power which an engine would produce if all the energy of combustion released inside the cylinders were converted into useful power. This power is measured by means of an engine *indicator* which automatically records the pressure exerted on the piston during all the stages of its power stroke. This pressure averages as much as 120 lb. per sq. in. in many airplane engines. The indicated H.P. can be calculated by the use of the following formula:

$$\text{I.H.P.} = \frac{\text{PLANK}}{33000}$$

where P = *average pressure during the power stroke in pounds per square inch.*
L = *length of stroke in feet.*
A = *area of cylinder in square inches.*
N = *number of power strokes per minute.*
K = *number of cylinders.*

2. MULTICYLINDER ENGINES

Overlapping power. Some internal-combustion engines have even more than sixteen cylinders. Let us now investigate the reason for multicylinder engines. It was shown in the discussion of how the four-cycle gas engine works that power was delivered by a single cylinder during one of the four cycles or strokes. This represents one power stroke during two complete revolutions of the crankshaft.

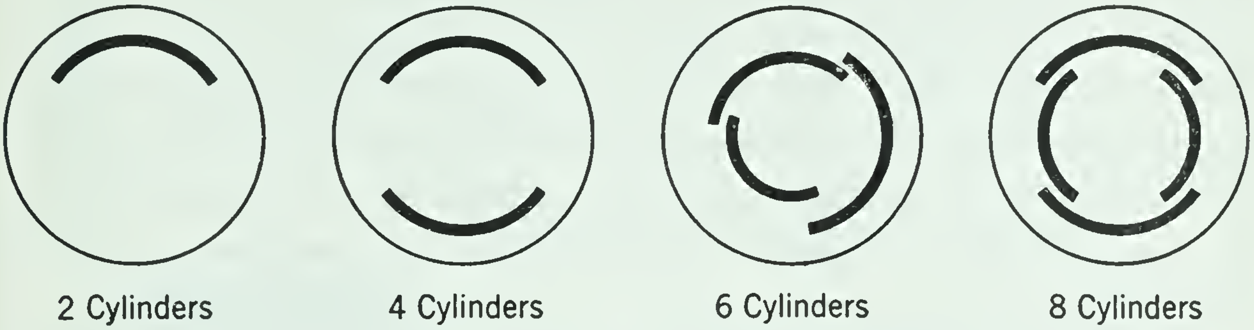


FIG. 14–11. Simple diagram of overlapping of power.

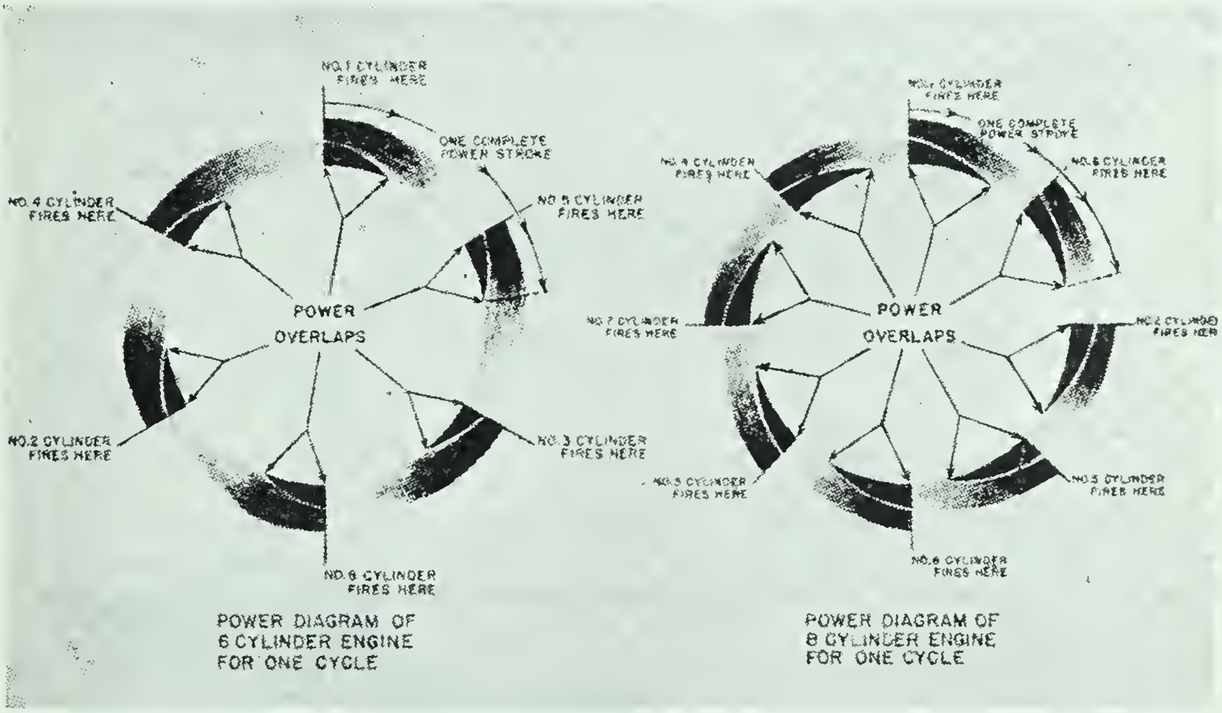


FIG. 14–12. Overlapping of power on 6-cylinder and 8-cylinder engines, showing the order in which the cylinders fire.

Actual tests show that effective power is produced through only about four-fifths of the expansion stroke. This means that for a single cylinder power is applied to the piston an average of two-fifths of a revolution once every two revolutions of the crankshaft or one-fifth of each single revolution. In a two-cylinder engine the duration of power application should average two-fifths of each single revolution; for a four-cylinder engine it should average four-fifths of a single revolution; and for a six-cylinder motor the average should be six-fifths of a single revolution. In the latter case there are intervals during the single revolution when two cylinders are exerting power simultaneously. This is shown as *overlapping of power.* (See Figs. 14–11 and 14–12.) As the number of cylinders increases the overlapping of power increases.

The relation of power strokes to each other in multiple cylinder engines (see Fig. 14–10) is shown diagrammatically in Figures 14–13 to 14–17, inclusive. From these diagrams it can be seen that for engines of more than eight cylinders there would be an overlap between three cylinders.

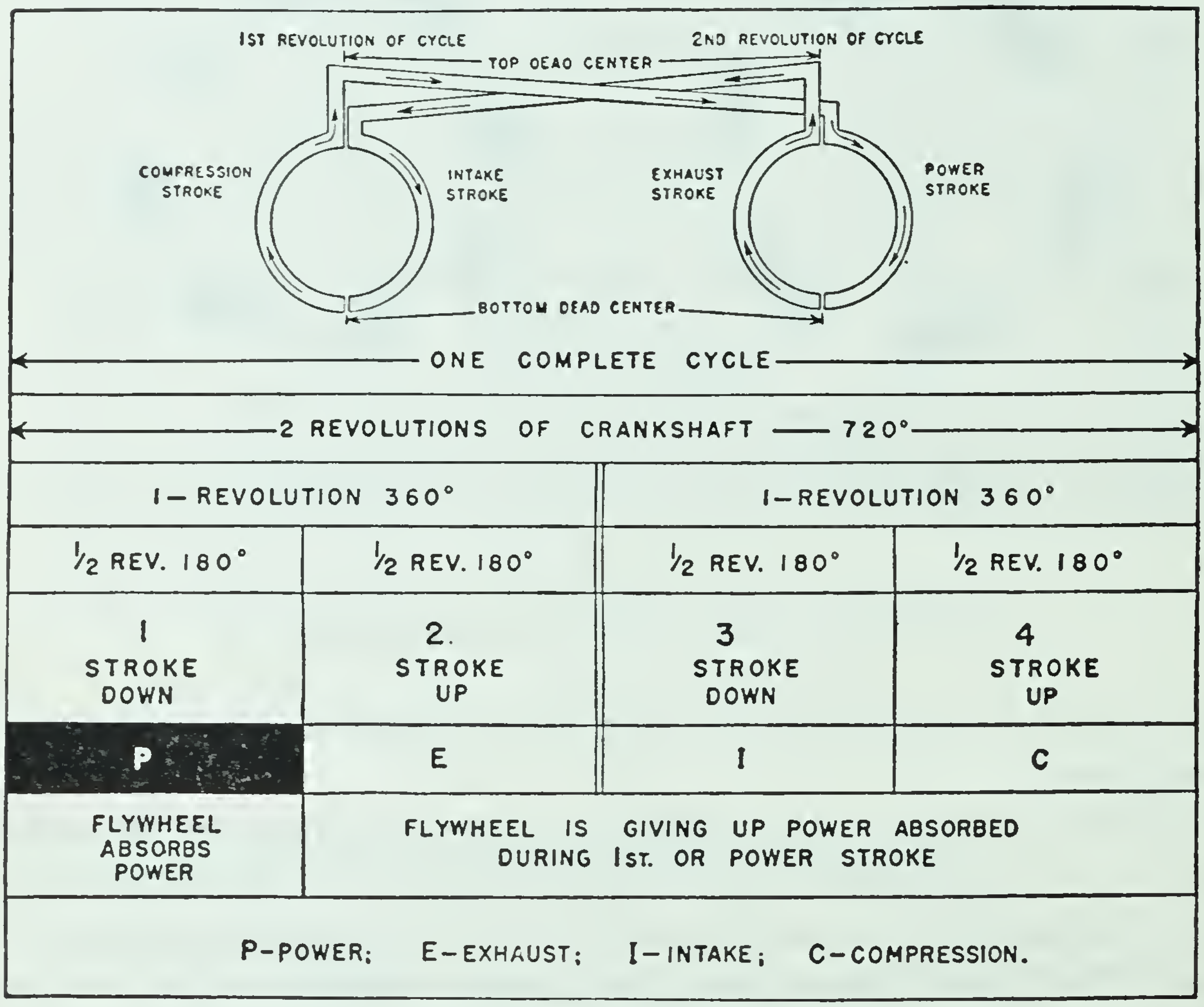


Fig. 14–13. One-cylinder engine.

FIRING ORDER OF CYLINDERS	ONE COMPLETE CYCLE			
	2-REVOLUTIONS OF CRANKSHAFT — 720°			
	1-REVOLUTION 360°		1-REVOLUTION 360°	
	½ REV. 180°	½ REV. 180°	½ REV. 180°	½ REV. 180°
	1 STROKE DOWN	2 STROKE UP	3 STROKE DOWN	4 STROKE UP
1	P	E	I	C
2	I	C	P	E
P-POWER; E-EXHAUST; I-INTAKE. C-COMPRESSION				

FIG. 14–14. Two-cylinder engine.

FIRING ORDER OF CYLINDERS	ONE COMPLETE CYCLE			
	2-REVOLUTIONS OF CRANKSHAFT — 720			
	1-REVOLUTION 360		1-REVOLUTION 360	
	½ REV 180	½ REV. 180	½ REV. 180	½ REV. 180
	1 STROKE DOWN	2 STROKE UP	3 STROKE DOWN	4 STROKE UP
1	P	E	I	C
3	C	P	E	I
4	I	C	P	E
2	E	I	C	P
P-POWER, E-EXHAUST; I-INTAKE; C-COMPRESSION.				

FIG. 14–15. Four-cylinder in-line engine.

FIRING ORDER OF CYLINDERS	ONE COMPLETE CYCLE											
	2—REVOLUTIONS OF CRANKSHAFT — 720°											
	1—REVOLUTION — 360°						1—REVOLUTION — 360°					
	½ REV. 180°			½ REV. 180°			½ REV. 180°			½ REV. 180°		
	1 STROKE DOWN			2 STROKE UP			3 STROKE DOWN			4 STROKE UP		
	60	60	60	60	60	60	60	60	60	60	60	60
1	P	P	P	E	E	E	I	I	I	C	C	C
5	C	C	P	P	P	E	E	E	I	I	I	C
3	I	C	C	C	P	P	P	E	E	E	I	I
6	I	I	I	C	C	C	P	P	P	E	E	E
2	E	E	I	I	I	C	C	C	P	P	P	E
4	P	E	E	E	I	I	I	C	C	C	P	P

P-POWER; E-EXHAUST; I-INTAKE; C-COMPRESSION.

Fig. 14–16. Six-cylinder in-line engine.

FIRING ORDER OF CYLINDERS	ONE COMPLETE CYCLE																			
	2-REVOLUTIONS OF CRANKSHAFT —— 720°																			
	1-REVOLUTION OF CRANKSHAFT 360°										1-REVOLUTION OF CRANKSHAFT 360°									
	½ REV. 180°					½ REV. 180°					½ REV. 180°					½ REV. 180°				
	1 STROKE DOWN					2 STROKE UP					3 STROKE DOWN					4 STROKE UP				
	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°	36°
1	P	P	P	P	P	E	E	E	E	E	I	I	I	I	I	C	C	C	C	C
3	C	C	C	C	P	P	P	P	P	E	E	E	E	E	I	I	I	I	I	C
5	I	I	I	C	C	C	C	C	P	P	P	P	P	E	E	E	E	E	I	I
2	E	E	I	I	I	I	I	C	C	C	C	C	P	P	P	P	P	E	E	E
4	P	E	E	E	E	E	I	I	I	I	I	C	C	C	C	C	P	P	P	P

P-POWER; E-EXHAUST; I-INTAKE; C-COMPRESSION.

Fig. 14–17. Five-cylinder radial engine.

FIRING ORDER OF CYLINDER "V-TYPE" ENGINE	FIRING ORDER OF CYLINDER "IN-LINE" ENGINE	ONE COMPLETE CYCLE															
		2 REVOLUTIONS OF CRANKSHAFT — 720°															
		1-REVOLUTION OF CRANKSHAFT 360°								1-REVOLUTION OF CRANKSHAFT 360°							
		½ REV. 180°				½ REV. 180°				½ REV. 180°				½ REV. 180°			
		1ST. STROKE DOWN				2ND. STROKE UP				3RD. STROKE DOWN				4TH. STROKE UP			
		45°	45°	45°	45°	45°	45°	45°	45°	45°	45°	45°	45°	45°	45°	45°	45°
1R	1	P	P	P	P	E	E	E	E	I	I	I	I	C	C	C	C
1L	6	C	C	P	P	P	P	E	E	E	E	I	I	I	I	C	C
4R	2	C	C	C	C	P	P	P	P	E	E	E	E	I	I	I	I
4L	5	I	I	C	C	C	C	P	P	P	P	E	E	E	E	I	I
2L	8	I	I	I	I	C	C	C	C	P	P	P	P	E	E	E	E
3R	3	E	E	I	I	I	I	C	C	C	C	P	P	P	P	E	E
3L	7	E	E	E	E	I	I	I	I	C	C	C	C	P	P	P	P
2R	4	P	P	E	E	E	E	I	I	I	I	C	C	C	C	P	P

P—POWER; E—EXHAUST; I—INTAKE; C—COMPRESSION
R OR L INDICATES RIGHT OR LEFT BANK OF CYLINDERS

FIG. 14–18. Eight-cylinder engine.

E. FUEL SYSTEM—VENTURI TUBE AND BERNOULLI'S PRINCIPLE

1. GASOLINE FEED

How does gasoline get to the engine? In early models, the gasoline tank was under the front seat and the gasoline flowed down to the carburetor by gravity. Later, a vacuum tank was used. Now nearly all cars have a fuel pump to pump the gasoline from the tank in the rear through a metal pipe beneath the car to keep the carburetor supplied.

What is the purpose of the carburetor? Contrary to popular belief, *liquid* gasoline does not explode. *Gasoline vapor does not explode, unless it is mixed with air.* When mixed with air in the proper proportion, gasoline vapor forms an explosive that is many times as powerful as an equal weight of dynamite. The carburetor is designed to vaporize the gasoline and mix it with enough air to form an explosive mixture. An *ideal* carburetor should be so constructed that it will vaporize every drop of gasoline and mix it with enough air to burn completely every molecule of the vapor. For three reasons, such a carburetor is impossible.

(1) Gasoline is a mixture of varying composition. One sample may need 47 parts of air to one of vapor for complete combustion, and another sample may require 60 parts of air.

(2) Perfect vaporization cannot be secured until the engine warms up, and a richer mixture of gasoline is needed for starting.

(3) A carburetor that is adjusted for one speed of operation is not perfectly adjusted when the engine is running more rapidly.

2. CARBURETOR

Bernoulli's principle again. In your study of Bernoulli's principle (page 178) you learned that the operation of the atomizer, aspirator, and carburetor depends upon the fact that if at a given point the speed of a liquid or gas increases, the pressure at that point decreases. You learned also that a tube with a constriction made for the purpose of increasing the velocity of a fluid effects a reduction in pressure at the

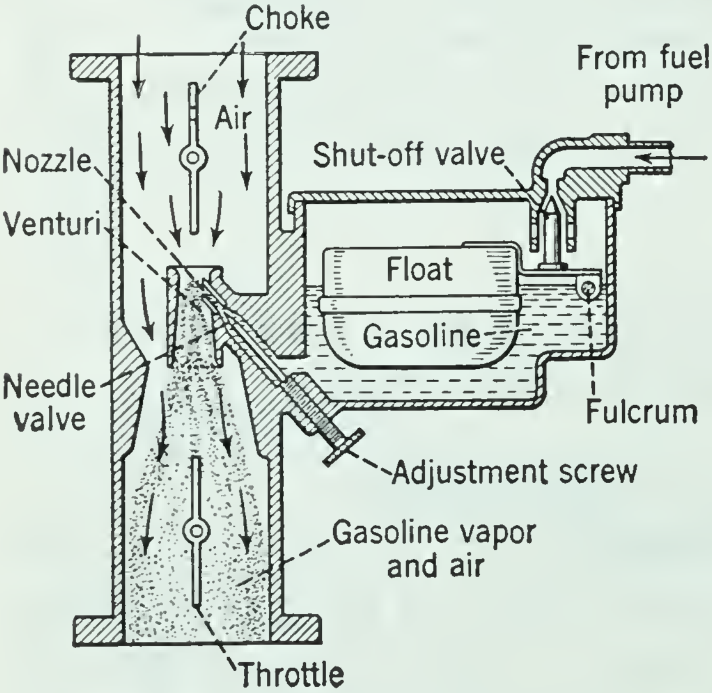


FIG. 14–19. The carburetor vaporizes the gasoline and mixes it with air to form an explosive mixture. Downdraft type.

constricted point. Let us review now the operation of a simple carburetor. (Fig. 14–19.)

One part of the carburetor consists of a gasoline well, which is kept filled to the level shown in the figure by means of a float which controls the needle valve at the end of the tube leading from the gas supply tank. When the engine operates, a partial vacuum is produced in the chamber shown in the figure. The throttle is opened. Air entering in the direction shown by the arrows sweeps past the end of the nozzle and mixes with the gasoline vapor which is escaping from it. The space around the nozzle is narrowed so that the air will have a greater velocity. An auxiliary valve may be used to open automatically and admit more air when the engine is running rapidly.

What is the purpose of the choke? A mixture of gasoline vapor and air containing more gasoline vapor than is necessary to form an explosive mixture is often called a "rich" mixture. One containing a larger proportion of air is called a "lean" mixture. It is economical to have the carburetor so adjusted that the engine will run on the "leanest" possible mixture. Such an engine stalls easily, and it is hard to start in cold weather. A choke may be used to shut off some of the air supply entering the carburetor and give a richer mixture.

The choke should be used in starting. Then the choke button should be pushed back again to admit free entrance of air as soon as the engine is warmed up. On many new cars the choke is automatically operated. It is wasteful to use the choke after the engine is warmed up, and it fouls the cylinders of the engine. It is not a good plan to use the choke to stop the engine in the evening in order to have it start more easily the next morning, because the vapor will condense on the cylinder walls and dissolve the oil film which keeps them lubricated. In that way the walls might be scored.

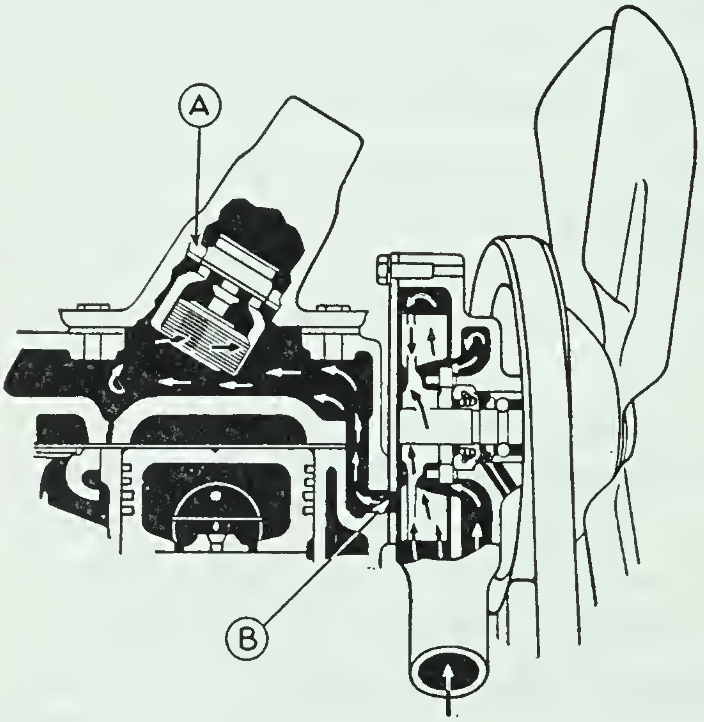
F. COOLING SYSTEMS

(Review Chapter XII for conduction, convection, and radiation)

1. LIQUID-COOLED ENGINES

The most common method of cooling. In studying the internal-combustion engine, you learned that it is necessary to keep an engine reasonably cool. You already know that the most common method of cooling is to circulate water around the cylinders and through the head of the engine. From the cylinder, heat is transmitted through the cylinder wall to the water by conduction. The water is circulated either by convection or by a pump through the radiator where much of its heat is lost by radiation as well as conduction to the surrounding air.

There is not likely to be much trouble with the water-cooling system in summer, but winter brings its problems. A thermostat remains closed until a small quantity of water is warmed and then opens to permit the water to circulate around the radiator. (See Fig. 14–20.) This permits the engine to warm up quickly. If the water freezes, it may burst the cylinder head, the water jacket, or the radiator. Hence, an *antifreeze* solution is necessary. An ideal antifreeze solution does not rust the metal parts or destroy the rubber connections. It must have a low freezing point. It must not boil away too rapidly.



Courtesy of the General Motors Corporation

FIG. 14–20. The thermostat is shown here in the closed position, and only a small amount of water is being warmed. When it opens, the circulation becomes general.

A mixture of alcohol and water is not very expensive, and it has a low freezing point. It does not corrode the metal parts, but it may spoil the finish of the car if it overflows and comes into contact with the lacquered parts. Unfortunately, it boils away quickly, and it boils away faster than water does. Hence, a motorist may have a sufficient proportion of alcohol in the radiator mixture before starting on a trip, but boil away so much alcohol during the trip that the freezing point of the mixture becomes too high. A mixture of 30% *alcohol* and 70% *water* has a freezing point of about − 1° F.

Glycerine and water make a fairly satisfactory antifreeze solution. The glycerine does not boil away. It does attack rubber hose connections, however, and it leaks through such tiny openings that it is difficult to prevent loss of the solution by leakage. It is difficult to believe that the viscous glycerine will go through a smaller opening than alcohol will, but it is true. Glycerine is rather expensive, too. A rather permanent mixture containing 15% *alcohol*, 15% *glycerine*, and 70% *water*, freezes at − 5° F. Government authorities have recommended the use of *ethylene glycol* as an antifreeze that is as satisfactory as glycerine, and less expensive.

2. AIR-COOLED ENGINES

Air-cooled motors can be lighter for their horsepower. We have already seen (page 420) that a second method of cooling a motor is the air-cooled system. The heat from the cylinder is conducted through the cylinder wall to fins which increase the outside surface area. This increased area permits more area over which radiation can take place, also faster loss of heat by conduction to air.

Motorcycle engines and many aircraft engines use the air-cooled system since the motors can be made lighter in weight, for their horsepower, than can liquid-cooled motors.

G. SIMPLE MACHINES IN THE AUTOMOBILE

The automobile is a combination of simple machines. One of the most common examples of compound or complex machines is the automobile. In it we find many combinations of simple machines. The principle of the lever is found applied in such parts as the hand brake (Fig. 14–2), brake and clutch pedals (Fig. 5–23), and gearshift arm and linkage (Fig. 14–21). The wheel-and-axle principle is found in the crankshaft of the motor (Figs. 14–5 and 14–6), the steering wheel and shaft (Fig. 14–21), and the rear axle and wheels (Fig. 14–32). The fan and belt as well as the generator and belt illustrate the simple pulley (Fig. 14–2). Use is made of the screw in the lower steering mechanism of a car as well as in the differential of some low-speed trucks and tractors.

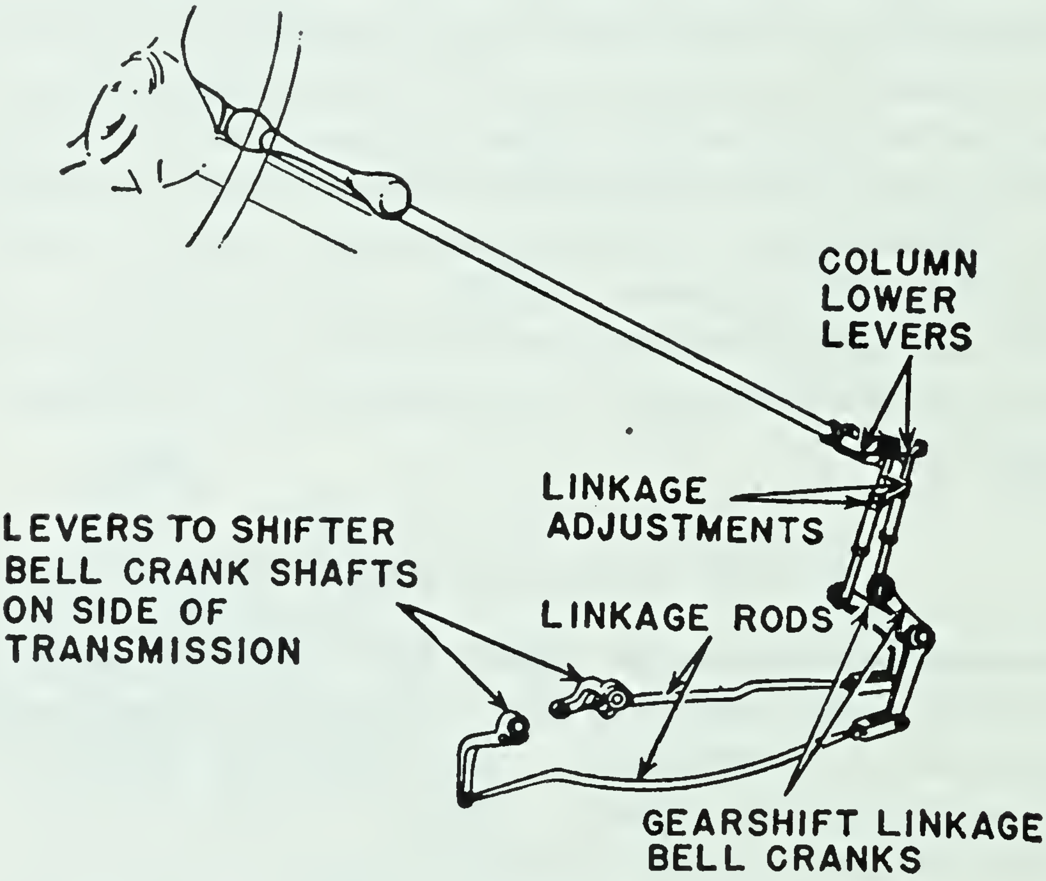

COLUMN LOWER LEVERS
LINKAGE ADJUSTMENTS
LEVERS TO SHIFTER BELL CRANK SHAFTS ON SIDE OF TRANSMISSION
LINKAGE RODS
GEARSHIFT LINKAGE BELL CRANKS

Fig. 14–21. Gearshift arm and linkage.

H. COMPOUND MACHINES IN THE AUTOMOBILE

What part of an automobile is the chassis? By the *chassis* we mean the frame to which the body and the wheels are attached, and the various parts of the drive mechanism. Sometimes the power plant, which has been discussed, is also considered a part of the chassis.

As new models appear from year to year, one observes that automotive engineers have steadily been making improvements. The engine is cushioned to prevent vibration. It is suspended low in its frame to give greater "roadability." A balancer is used on the crankshaft to secure steady motion. The frame is made stronger than ever before, by the use of special steels that are not likely to break, and also by special methods of bracing. The X-type frame is particularly strong. (See Fig. 14–22.) Crosswise tubes and heavier bumpers give more protection. The box-type frame is now being used by some manufacturers. (See Fig. 14–23.) With little more weight than the older type of frame made from channel steel, the box-type frame is much stronger. The frame is

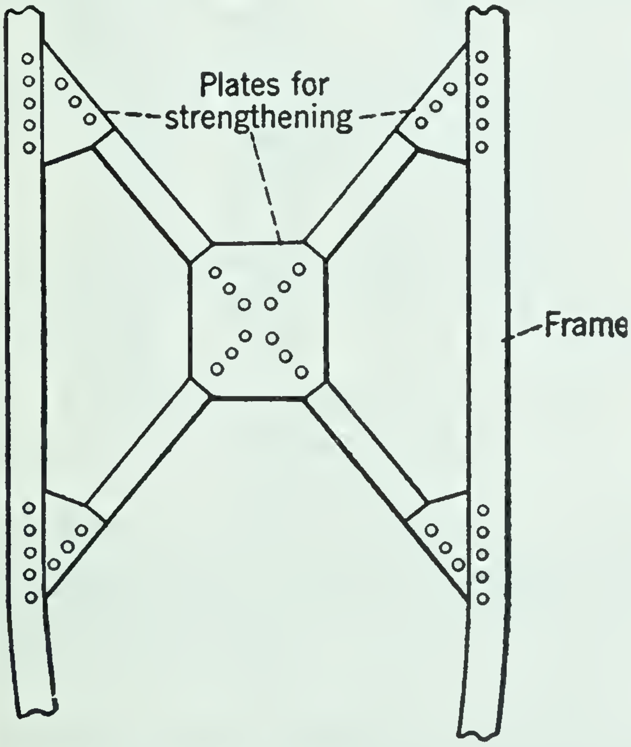


Fig. 14–22. The X-shaped frame is exceptionally strong.

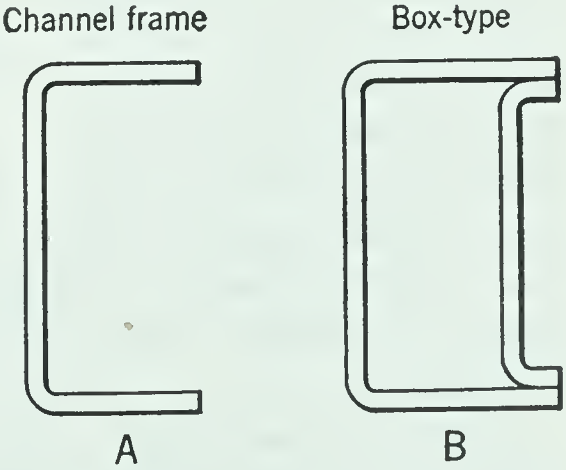


Fig. 14–23. The box-type of frame is stronger than the channel type.

underslung to give greater stability and make the car less likely to overturn when rounding a curve, or when standing on a slanting road.

What are transmission gears for? The throttle or accelerator is used to vary engine speed. Such control is satisfactory for driving on a level road. But to overcome the inertia of a car in starting or to drive the car up a steep hill, one needs a set of *transmission gears.* Most pleasure cars have three speeds forward and one speed in reverse.

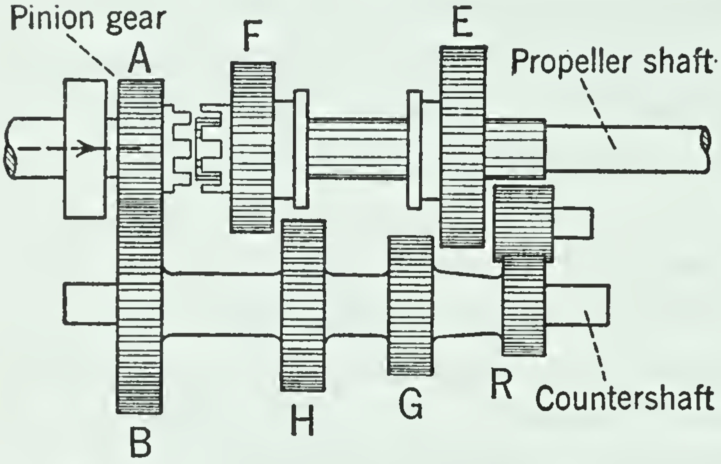


FIG. 14–24. Transmission gears in neutral.

The transmission system has three shafts: The pinion shaft, Figure 14–24, and the propeller shaft are both in the same straight line. The countershaft is always connected at one end to the pinion shaft, and it may be connected by means of sliding gears with the main drive shaft. The pinion shaft is connected to the engine through the clutch and it makes the same number of revolutions per minute as the crankshaft. Since the countershaft is geared to the pinion shaft, it is always in gear and it turns when the engine runs. The gear wheels, *E* and *F*, can be slid forward or backward along the drive shaft, which is square or grooved. Hence, when they turn, the main shaft must turn, too.

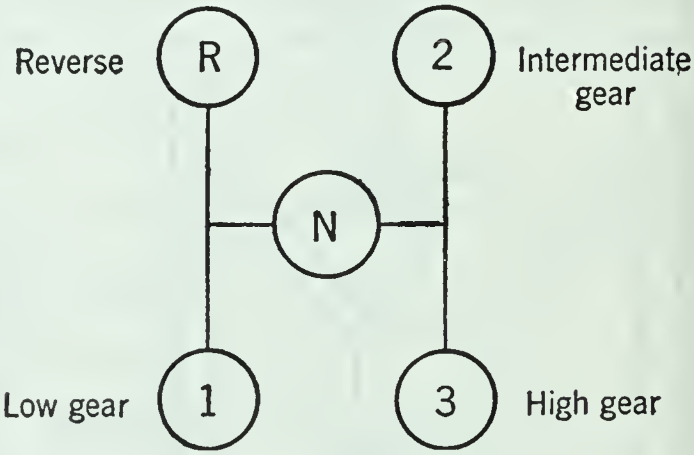


FIG. 14–25. H-shaped diagram to show gearshift.

Neutral. When starting the engine, the gearshift lever is at the position *N* of Fig. 14–25. The gears are then in the position as shown in Fig. 14–24. The pinion gear and the countershaft both turn. The pinion gear turns at the same speed as the crankshaft, but the countershaft may turn faster, more slowly, or at the same speed as the crankshaft, depending upon the relative number of teeth in each gear wheel. For example, suppose that there are 30 teeth in gear wheel *A* and 60 teeth in gear wheel *B*. Then the countershaft turns only one half as fast as the crankshaft. The drive shaft and the rear wheels do not turn, because its gears do not mesh with those of the countershaft.

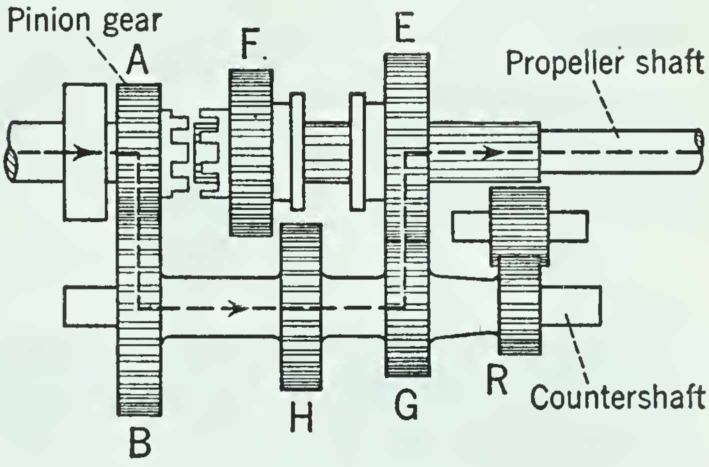


FIG. 14–26. Transmission gears for low speed.

First speed, or low speed. When the operator disengages the clutch and pulls the gearshift lever back to the position (1) of Fig. 14–25, he slides the gear *E* forward until it meshes with the small gear *G* on the countershaft. (See Fig. 14–26.) Suppose that *E* has 40 teeth and *G* has only 20 teeth. Then the drive shaft will make only half as many revolutions per minute as the countershaft, and only one fourth as many revolutions per minute as the crankshaft of the engine. We have two gear reductions, and the car is in *low gear*. At a given engine speed, it travels slowly. The power in this case is transmitted through *A*, *B*, *G*, and *E* to the drive shaft, as shown by the dotted lines.

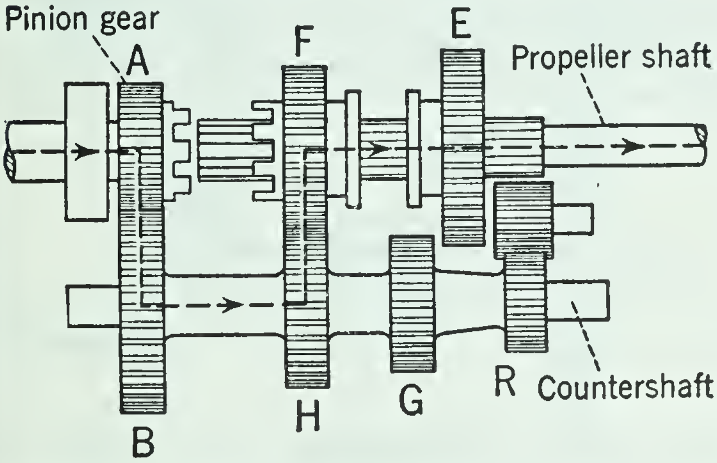


FIG. 14–27. Transmission gears for intermediate speed.

Second speed, or intermediate speed. As the gearshift lever is shoved forward and slightly from the driver to position (2), Figure 14–25, it moves the gear wheel *E* backward, and at the same time it moves the gear wheel *F* back until it meshes with the gear wheel *H*. (See Fig. 14–27.) Suppose that gear wheels *F* and *H* both have the same number of teeth, then the countershaft and the drive shaft will both make the same number of revolutions per minute, both of them just half as many as the crankshaft. The dotted line shows how the power is transmitted through gear wheels *A*, *B*, *H*, and *F* to the drive shaft.

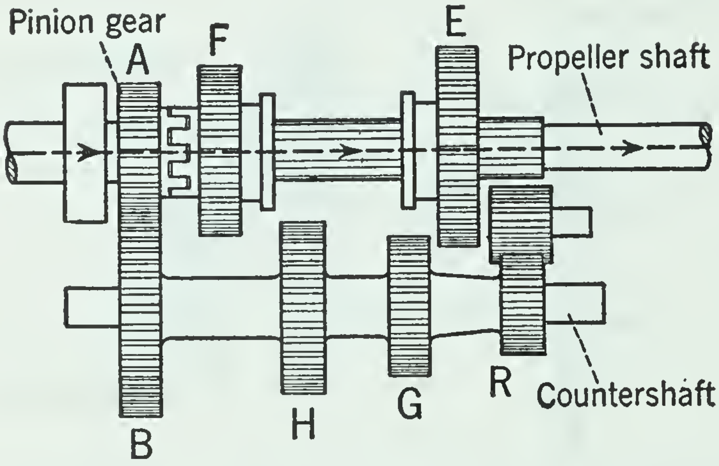


Fig. 14–28. Transmission in high gear.

Third speed, or high speed. When the gearshift lever is pulled back to position (3), Fig. 14–25, gear wheel *F* is pushed forward until it is locked to the pinion gear by means of teeth on the sides of the two gear wheels. (See Fig. 14–28.) The drive is now direct through the crankshaft and the drive shaft to the rear wheels. Both make the same number of revolutions per minute. The countershaft is idling.

Reverse speed. When the operator of a car pushes the gearshift lever forward to the position *R*, Figure 14–25, then the sliding gear wheel *E* meshes with a small idler gear and the gear *R*. Three gears are now meshed as shown in Figure 14–29. The pupil will observe that the crankshaft turns in the same direction as before, but the propeller shaft turns in the opposite direction.

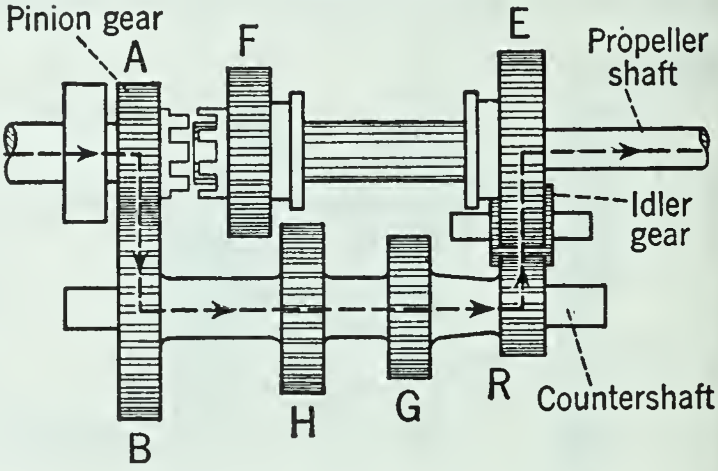
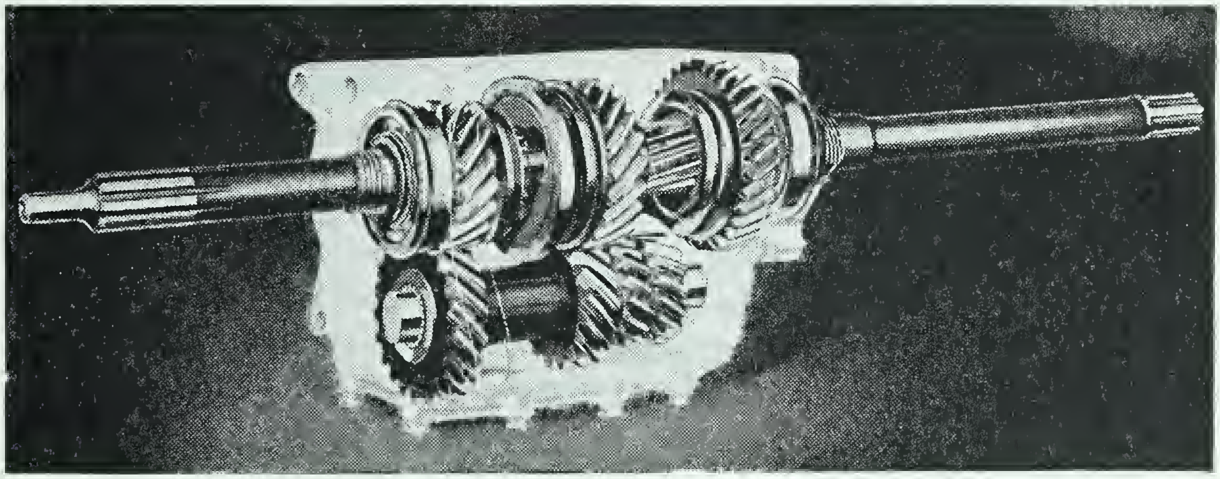


Fig. 14–29. Transmission gears in reverse.

What is synchro-mesh transmission? In shifting gears with the conventional transmission, the teeth sometimes "clash" or "grate," because it is difficult to "mesh" quietly the gears of two wheels traveling at different rates of speed. With *synchromesh* transmission the intermediate gears are always meshed, and the intermediate gear revolves on a bronze bushing, which turns with the drive shaft. (See Fig. 14–30.) To engage this gear wheel a slider coupling with teeth on the outside is used. When shifting into intermediate gear, these teeth mesh with gears cut internally on the intermediate gear wheel. A cone-type clutch is used to bring the two gears up to the same speed, or to synchronize them, before they are engaged. To secure more quiet operation when driving in second gear, bevel gears are used.



Courtesy of the General Motors Corporation

FIG. 14–30. Synchromesh transmission gears.

A second cone-type clutch is used to synchronize the slider coupling gear before shifting into high speed. The mechanism for shifting into low speed or into reverse is the same as that used with the conventional gearshift.

What is the differential? The transmission system is connected with the *differential* on the rear axle by means of two universal joints and the drive shaft. (See Fig. 14–30.) In rounding a corner, the outer wheel of a car must travel faster than the inside wheel. Since the driving power of the engine is transmitted to the rear axle, a device must be used so that the two rear wheels will both drive together; and it must permit one wheel to travel faster than the other on curves. The *differential*, which is placed between the two parts of the divided rear axle, accomplishes both of these purposes. (See Fig. 14–31.) The driving pinion, *A*, which is attached to the drive shaft, rotates the bevel gear, *B*, which is rigidly attached to the frame, *F*, and through the frame to the gears *C* and *E*. These parts must all rotate as a unit within the differential housing. On a straight road, the gears *C* and *E* do not rotate on their axes, but they are carried around with the frame, *F*. As they revolve with the frame, they turn the gears *D* and *G* at the same speed. These gears are attached to the inner ends of the divided rear axle. As they turn the axles, the rear wheels, which are rigidly attached to the other ends of these axles, drive the car. When the right axle turns faster than the left on a curve, then the gears *C* and *E* turn on their axes in opposite directions to compensate for the difference in speed of the two rear wheels. If one wheel stops, the other may continue to turn. A nonskid chain on one rear wheel is of no value on slippery roads. While one wheel grips, the other spins around rapidly, but the car does not move.

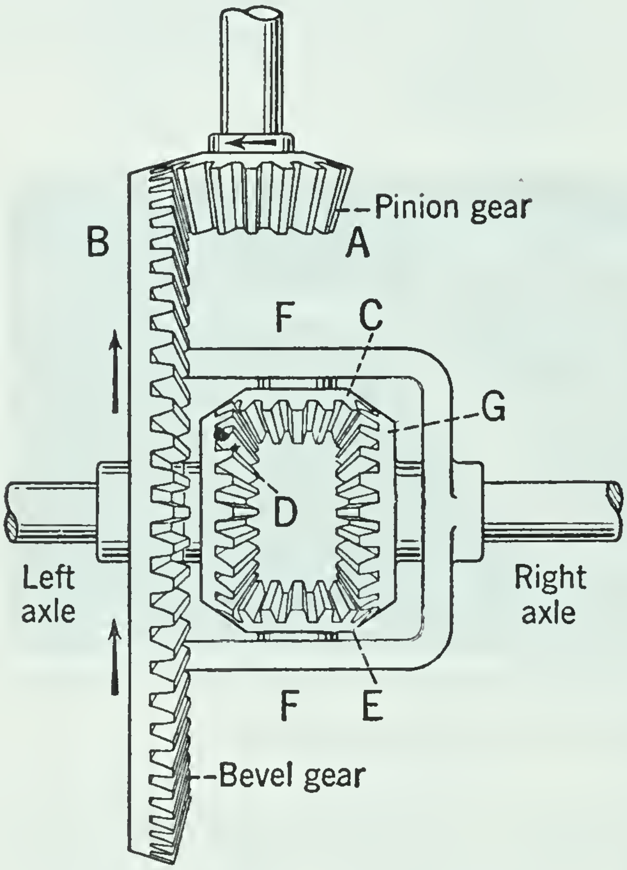
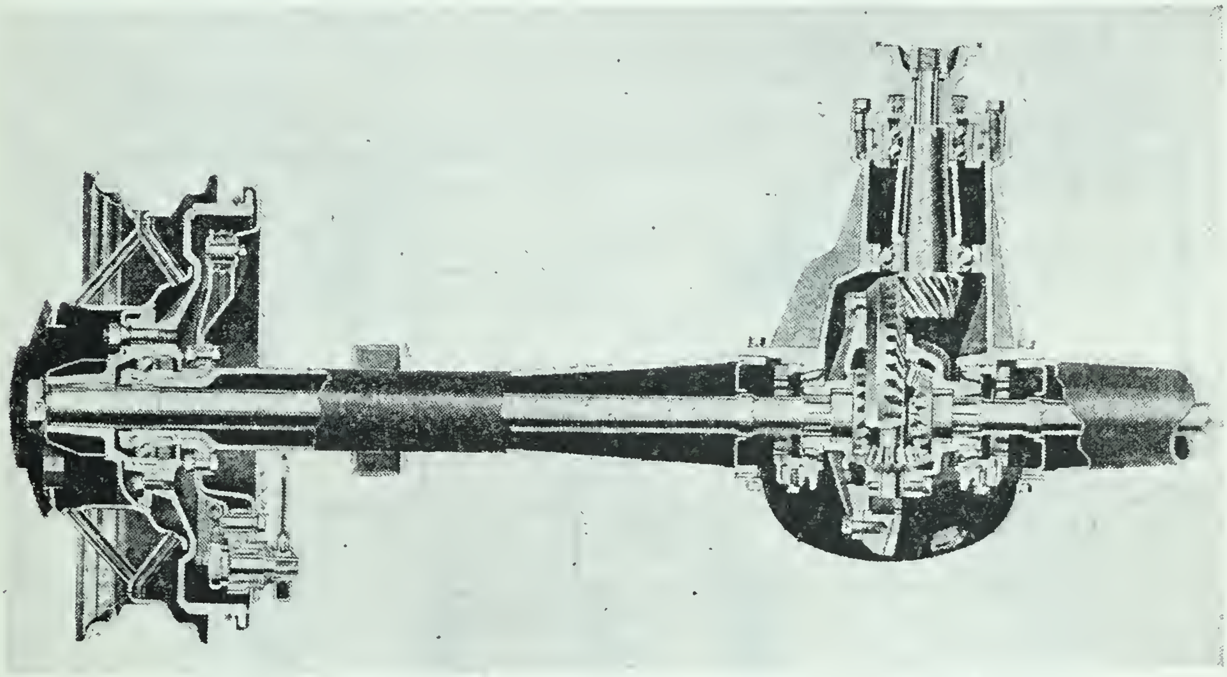


Fig. 14–31. Diagram of differential gears.

We have already seen how the speed may be varied by means of transmission gears. There is a gear reduction in the differential. If the pinion gear has 15 teeth and the bevel gear has 65, then at high speed the engine will be making 65 revolutions while the rear wheels are making only 15. The *gear ratio* on such a differential is 4.33 to 1. Figure 14–32 shows a sectional view of a rear axle with the housing cut away to show the differential. Some cars use a *dual gear ratio* in the differential. It is then possible to use one ratio to travel at very high speed and still have the engine revolving rather slowly. The other ratio is used for hills or for slow driving.

What are the parts of the ignition system? In the operation of a gas engine, the spark must occur at just the right time to ignite the explosive mixture. It must also occur in the proper cylinder. To accomplish this, a *timer* and *distributor* must be used. A battery system is generally used with a spark coil to produce the spark needed for ignition. A storage battery, which is charged while the engine is running, supplies the necessary current.



Courtesy of Cadillac Motor Car Company

FIG. 14–32. Differential and rear axle.

In Figure 14–33 we have given a six-volt battery. One terminal is connected to the metal frame and to the engine; the other terminal is connected by means of the switch with the primary of an induction coil. The timer is used to "break" the circuit in the primary and thus induce a high voltage in the secondary coil. One terminal of the secondary coil is grounded and the other terminal is connected to the rotor, one part of the distributor. As this rotor makes contact with the metal segment the induced voltage is high enough to cause a spark to leap across the gap between the two terminals of the spark plug in cylinder two.

The diagram shows how each of the four cylinders will fire in turn. As the cam *A* of the timer rotates, it will break the circuit four times during one revolution. The condenser is used to fatten the spark. The fiber ring is made of insulating material, but each one of the metal segments is connected with a spark plug. As the rotor turns in the direction shown by the arrow, a spark will be produced in the spark plugs in turn as it makes contact with the metal segments successively. Both the timer and distributor are geared with the engine so that the timing will be perfect. Generally, both are set on the same shaft. They are geared to rotate just half as fast as the crankshaft, since an explosion occurs once in two revolutions. (See Fig. 14–34.)

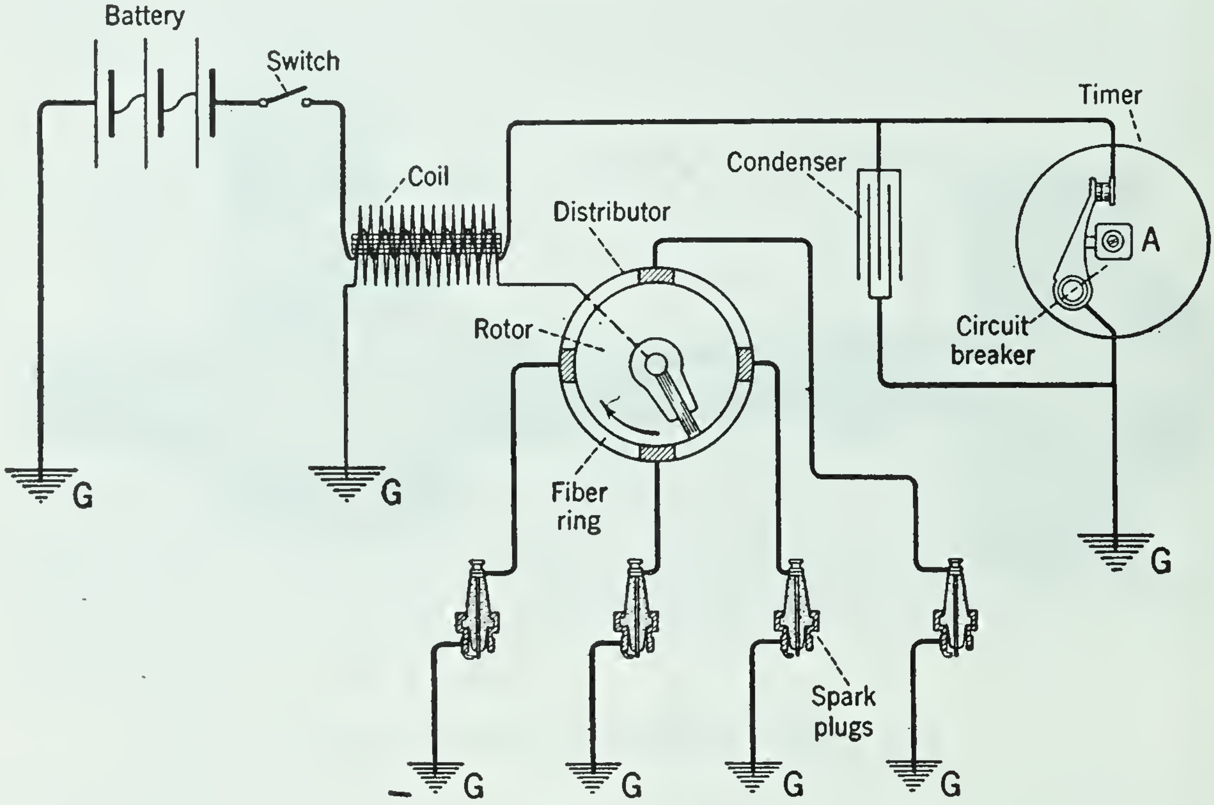
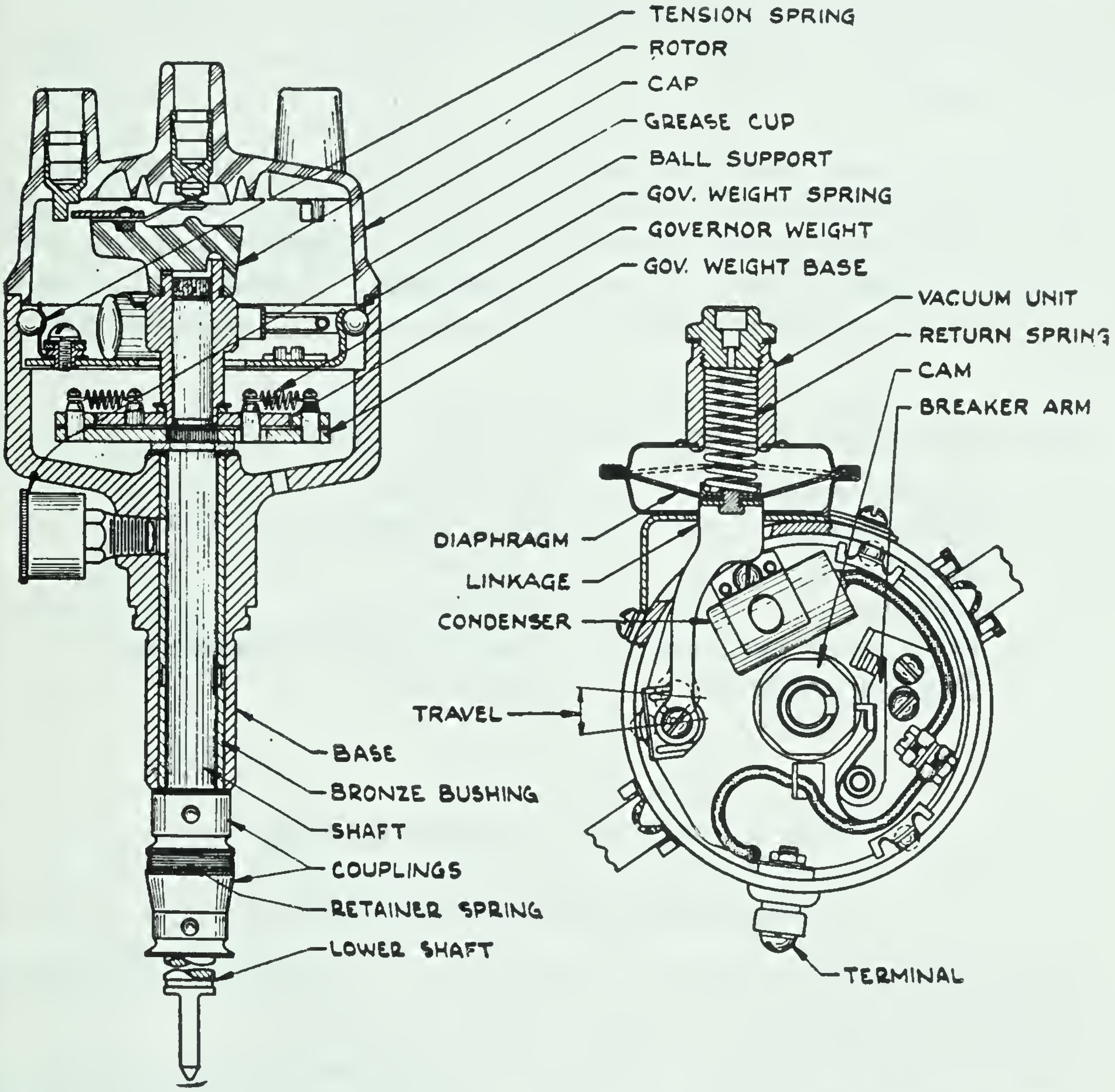


Fig. 14–33. Diagram showing the use of timer, coil, and distributor.

The combustion of the gasoline mixture is not instantaneous. When the engine is running fast, the time required for the complete combustion may be so long comparatively that the gas is not completely burned before the power stroke is completed. Then some of the unburned gas will escape through the exhaust. This difficulty is met by *advancing the spark* a few degrees so that the explosion will occur a little before the piston starts its working stroke. In order to give a fraction of a second more time for the gas to burn, it is ignited by the advanced spark before the compression stroke is quite finished. The spark is advanced by shifting the fiber ring so that it is rotated a few degrees in a direction opposite to that of the moving rotor. Thus the segments on the ring make contact with the rotor more quickly. Shifting the fiber ring in the opposite direction *retards* the spark. In the later models, the advancement and retardation of the spark are automatic.



Courtesy of the General Motors Corporation

FIG. 14–34. The distributor is usually mounted on the engine.

The body of the car must be strong. The all-steel body used on the modern car is designed to give greater strength and insure greater safety. The body is hung on an "underslung" chassis to give greater stability. The windshield is made slanting to reduce the amount of light reflected into the eyes of the driver. The nonshatter glass is a safety factor. The streamlined body reduces wind resistance.

DEMONSTRATION. The automobile embodies many principles of machines. If an autoshop is available, examine as many parts discussed in this chapter as possible. Otherwise, charts, diagrams, and any available parts should be used for review purposes. A neighboring repair shop or junk yard may co-operate in obtaining parts or in actual instruction.

How many of the following terms can you define or explain?

Shock absorber
Knee action
Fluid drive
Chassis
Four-stroke cycle engine
Overlapping power
Carburetor
Lean mixture
Choke
Transmission
Synchromesh transmission
Differential

SELF-TESTING EXERCISES

COMPLETE THESE STATEMENTS

On a separate sheet of paper numbered from 1 to 8 write the words needed to fill correctly the blank spaces in the following sentences.

Shock absorbers assist the springs in absorbing jolts, and overcome the tendency of the car to ..(1)... Individual wheel suspension is sometimes called ..(2)... The ..(3).. makes possible a variable speed connection between the motor and the rear wheels of the car. In some multicylinder engines there are intervals during a single revolution when two cylinders are exerting power at the same time. This is called ..(4).. of power. The purpose of the ..(5).. is to vaporize the gasoline and mix it with air. A mixture containing a large portion of air to a given amount of gasoline vapor is called a ..(6).. mixture. If a motor does ..(7).. foot-pounds of work per minute it is developing one horsepower. The more cylinders there are the greater the ..(8).. of the engine.

ARE THESE TRUE OR FALSE?

On a separate sheet of paper numbered from 1 to 12 write a T *or an* F *to show whether each statement is true or false.*

1. The channel-iron frame is stronger than the box-type frame.
2. Crosswise strength in the frame of a car is secured by X-plate bracing and by cross tubing.
3. The underslung chassis gives easier riding.
4. An 8-cylinder engine is always more powerful than a 6-cylinder engine.
5. In most cars gasoline gets to the carburetor by gravity feed.
6. When one pulls out the choke he cuts off the air supply.
7. The fluid clutch permits gentle starting with little or no gear-shifting.
8. When the car is in first gear the crankshaft makes fewer revolutions per minute than the driveshaft.
9. The distributor distributes the gasoline uniformly to each cylinder.
10. The differential permits one wheel to travel faster than the other.
11. In third speed the driveshaft and crankshaft revolve with the same speed.
12. Bevel gears are used for quiet operation.

QUESTIONS

1. Is a wheel a lever? Explain.
2. With the ordinary differential, is a chain on one rear wheel a help in starting a car in the snow or on slippery streets? Explain.
3. Refer to Figure 14–2 and pick out as many simple machines as you can.
4. How is it possible to use the engine as a "brake" in driving down a steep hill? Is it more effective in "high" or in "low" gear?
5. What advantages does an eight-cylinder engine have over a six-cylinder engine? Has it any disadvantages?
6. What is the purpose of the "choke valve" on a car? Why is the excessive use of the "choke" wasteful?
7. Is it possible for a four-cylinder engine to furnish more power than an eight-cylinder engine? Explain.
8. Why is it easier to steer a car if the steering wheel has a large diameter?
9. Why is it necessary to bring a car to a full stop before shifting into reverse gear?

10. Explain in considerable detail how the excess heat from the engine is removed.

11. How are airplane engines cooled?

12. What is meant by the expression "flooding" as applied to the carburetor and cylinders of an engine, and why is it impossible to start such an engine?

13. Why is it economical to drive a car at moderate speed, but wasteful to drive at high speed?

14. How does increasing the diameter of the brake drums on the wheels of a car affect the braking force?

15. What is the effect of "advancing" or "retarding" the spark in the operation of a gas engine?

16. What is the purpose of the clutch and how does it operate?

17. Why should the clutch be released before trying to start a gas engine in cold weather?

18. Show how inflating a tire exemplifies (*a*) heat by friction and compression; (*b*) molecular motion; (*c*) Pascal's law.

19. Is the energy in gasoline kinetic or potential? Discuss the transformations of energy involved in starting and running an automobile. (See Fig. 14–35.)

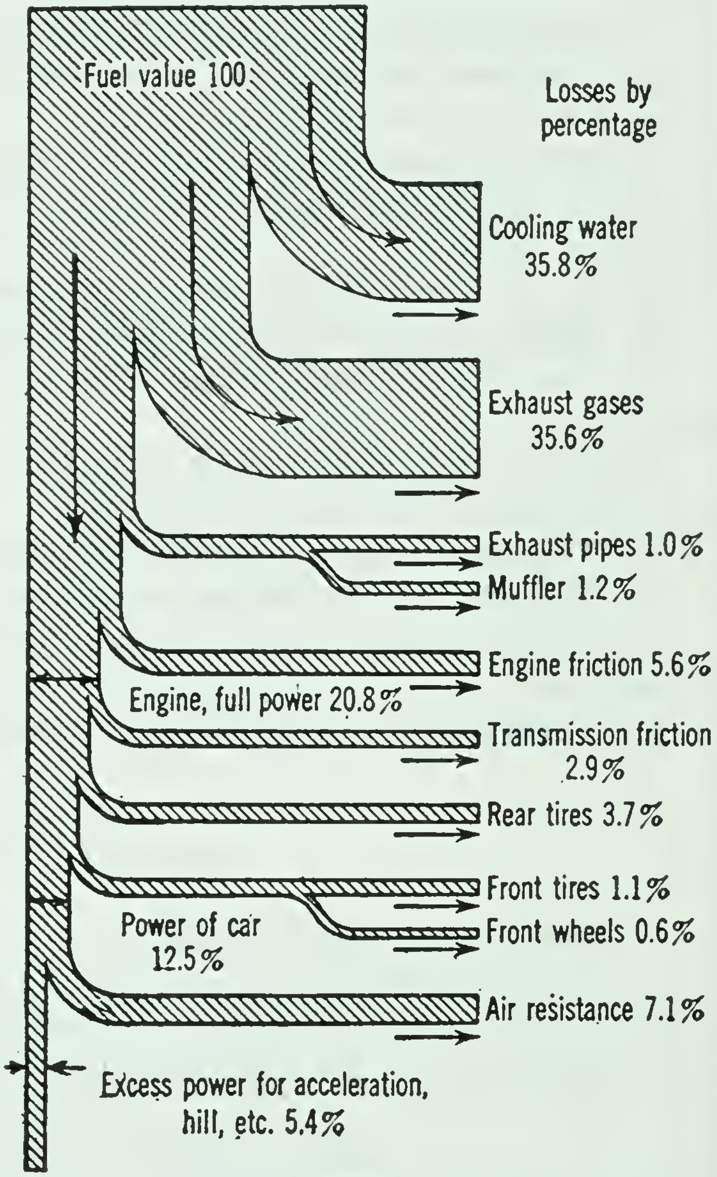


Fig. 14–35. Energy diagram for a car traveling about 40 miles per hour.

20. Will a car climb a hill more readily if fitted with rear wheels of 30″ or of 34″ diameter?

21. Why is steering difficult if the front tires are not both inflated to the same pressure?

22. What is the purpose of synchromesh transmission gears?

23. How is the flow of fuel from the tank in the carburetor regulated? (See Fig. 14–19.)

24. What advantage is there in having two different gear ratios in the differential of an automobile?

25. Why are modern cars streamlined?

26. Look up the subject of Diesel engines. Since they are economical to operate, why do you think that they are not used for modern pleasure cars?

LABORATORY EXPERIMENTS

Experiment 1

MEASUREMENT OF AREA AND VOLUME

USE OF THE METRIC SYSTEM

PURPOSE: (*a*) To find out how the area of a rectangular block can be accurately measured; and (*b*) to find out how the volume of a cylinder can be accurately measured.

APPARATUS: Section of a meter stick; vernier caliper; rectangular wooden block, about 3 × 3 × 1.5 inches; regular cylinder, preferably of brass or aluminum (about 2 or 3 inches long and 1 or 1.5 inches in diameter).

BACKGROUND: Because of its simplicity as a decimal system, the metric system is the one generally used in the laboratory. This experiment provides experience in the use of metric linear units, and practice in more accurate measurement of length or distance and diameter.

PROCEDURE:

1. Using the vernier caliper, find the length of the block of wood by measuring each of its four edges. It is unlikely that the block will be absolutely uniform; therefore each of these four measurements may be different. Enter them in the table which follows. The average of the four length measurements represents the most accurate length.
2. Measure the width of the block at each of its four edges and compute the average width.
3. Measure the thickness of the block at each of its four edges and compute the average thickness.
4. Find the area of one side of the block by multiplying the average length by the average width.
5. Find the volume of the block by multiplying the area of one side by the average thickness.
6. Measure the length and diameter of the cylinder. If a meter stick is used for this measurement, the diameter of the cylinder may be found by placing rectangular blocks on the sides of the cylinder as in Figure 1, and measuring the distance between them. To compute the volume of

the cylinder, multiply 0.7854 times the diameter squared by its length. Volume = $\frac{1}{4}\pi D^2L$, or πR^2L.

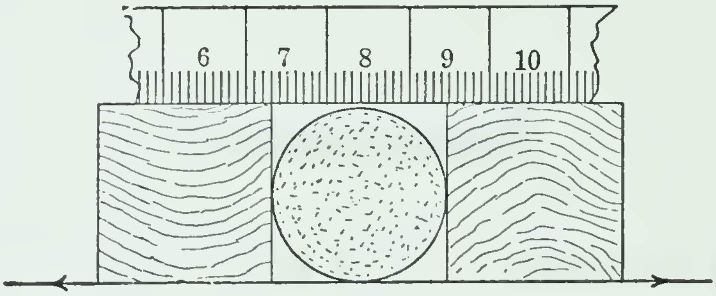


Fig. 1

Data: All measurements should be tabulated as follows. *Copy and complete the table; do not mark this book.*

Trial	Length of block	Width of block	Thickness of block	Length of cylinder	Diameter of cylinder
1					
2					
3					
4					
Average					

7. What is the area of block? What is the volume of block? What is the volume of cylinder?

Problems:

1. A glass cylinder 30 cm. long has an internal diameter of 5 cm. How many cubic centimeters does it hold?
2. Read the vernier scale on the laboratory barometer. Ask the instructor to verify your reading.

Experiment 2

DETERMINING DENSITY

PURPOSE: To find the average weight of one cubic centimeter of wood.

APPARATUS: Trip balance; set of metric weights; solids used in experiment 1.

BACKGROUND: Such solids as lead and iron are heavy; cork and charcoal are very light. By these statements we mean that a given volume of each of these substances has a different weight. There are more pounds in one cu. ft. of lead than there are in one cu. ft. of iron. The weight of unit volume of a substance is called its density. The volume generally used in the metric system is the cubic centimeter; in the English system the cubic foot is the most common unit. If the solids used in experiment 1 are used in this experiment, it will be unnecessary to redetermine their volume. If the instructor desires to have other solids used, their volume may be found by one of the methods given.

PROCEDURE:

Weigh the block of wood and the cylinder you used in experiment 1. Knowing the weight and the volume, it is easy to find the weight of *unit* volume. In the metric system, density equals $\frac{\text{gm.}}{\text{cc.}}$; in the English system density equals $\frac{\text{lb.}}{\text{cu. ft.}}$

DATA: *Copy the table; do not mark your book.*

Substance used	Volume (cc.)	Weight (gm.)	Density

PROBLEMS:

1. A cubic foot of a certain sample of hard coal weighs 90 lb. How many tons of coal can be put in a bin 10 ft. long, 8 ft. wide, and 5 ft. high?

2. Sand has a density of 125 lb. per cu. ft. A wagon-box is 10 ft. long, 3 ft. wide, and 16 in. deep. How many pounds of sand will the box hold, if it is level full?

Experiment 3

LEVERS AND PRINCIPLE OF MOMENTS

PURPOSE: (*a*) To find out what conditions are necessary to produce equilibrium in a lever; and (*b*) to find out how each of the three classes of levers works.

APPARATUS: Meter stick; clamps; support; set of weights; cord for suspension of weights; lever; scale pans; spring balances, 250 gm. capacity.

BACKGROUND: The effectiveness of a force in producing rotation depends upon two things: (*a*) the magnitude of the force; (*b*) the length of the arm upon which it acts. The product of force times distance to the axis is called the moment of force. When several parallel forces act upon a pivoted bar in a clockwise direction, the total effect will equal the sum of all their moments. To secure equilibrium, the sum of all the moments attempting to produce counterclockwise rotation must just equal the sum of all the clockwise moments.

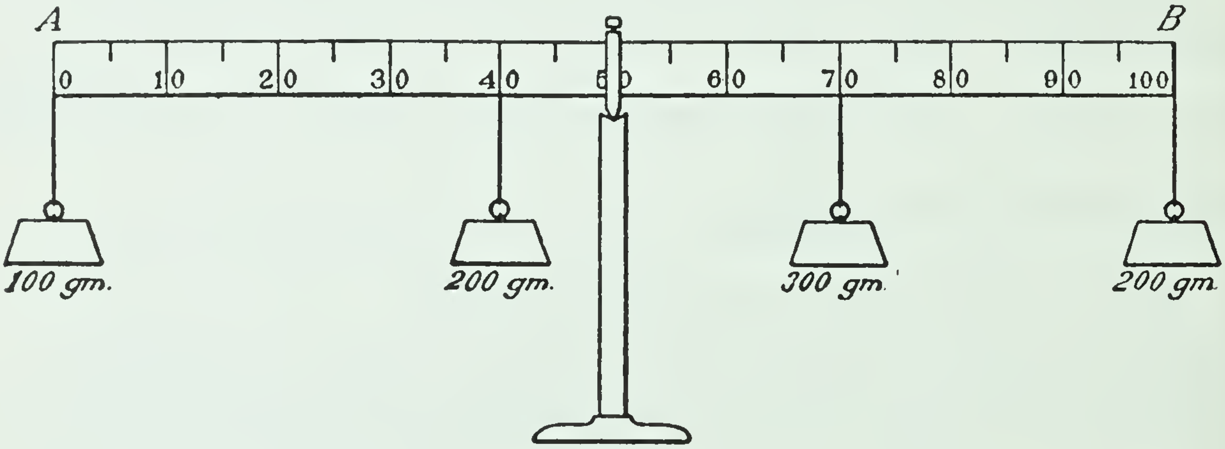


FIG. 2

PROCEDURE:

1. The bar of Figure 2 is supported at its center with the zero end at the left. Weights are hung from the bar or stick as follows: At the end *A*, 100 gm.; at the 40-cm. mark, 200 gm.; at the 70-cm. mark, 300 gm.; and at the end *B*, 200 gm. Find where a weight of 500 gm. must be placed to secure equilibrium.

2. For a second trial, place weights as follows: a 200-gm. weight at A; a 150-gm. weight at the 20-cm. mark; a 300-gm. weight at the 25-cm. mark; a 200-gm. weight at the 80-cm. mark; and a 400-gm. weight at the end B. Find what weight must be placed at the 40-cm. mark to secure equilibrium.

DATA: *Copy the table; do not mark your book.*

First trial		Second trial	
Clockwise moments	Counterclockwise moments	Clockwise moments	Counterclockwise moments
300×20= 6000 200×50=10000	100×50=5000 200×10=2000 500× . . = ...	400×50=20000 200×30= 6000	200×50=10000 150×30= 4500 300×25= 7500 . . . ×10= . . . . .
Sum	Sum	Sum	Sum . . . . .

BACKGROUND: The lever is one of the simplest types of machine. Known as early as the time of Archimedes, it was one of the first machines to be used. To-day we find the lever used in such devices as shears, can openers, nut-crackers, tongs, pump handles, brooms, shovels, etc. The mechanical advantage of any lever equals the length of the effort arm divided by the length of the resistance arm. When the lever is in equilibrium, the clockwise and counterclockwise moments are equal. When the effort arm exceeds the resistance arm in length, the lever is used to multiply force. When the resistance arm is longer than the effort arm, the lever is used to gain speed.

PROCEDURE:

1. *First-class.* Arrange the lever as shown in Figure 3 and clamp it firmly. Weigh the scale pan, unless its weight is known. Put a 200-gm. weight on the pan marked R and place the pan a few cm. (possibly 8 cm.) from the fulcrum. In recording the resistance R, the weight of the scale pan must be included. The distance of the resistance from the fulcrum is to be recorded as D_r. With a weight of 150 gm. in the other scale pan, slide it along the lever until equilibrium is secured. The effort (pan plus 150) is to be recorded in column E, and its distance from the fulcrum under D_e. Compute the moments of both the

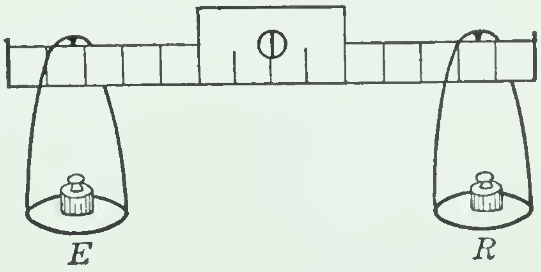


FIG. 3

effort and resistance, and find their difference. Find the mechanical advantage by dividing R by E, and also by dividing D_e by D_r. Carry two decimal places, and find the difference.

Repeat the experiment, using different weights in different positions.

2. *Second-class.* Put a 200-gm. weight in pan R of Figure 4, and place it 5 cm. from the fulcrum. Hook the spring balance at E, 12 cm. from the fulcrum, and pull it up until equilibrium is secured. Record E, R (weight plus pan), D_e, and D_r, and make all computations just as you did with the first-class lever. In repeating the experiment, use different weights and vary the distances.

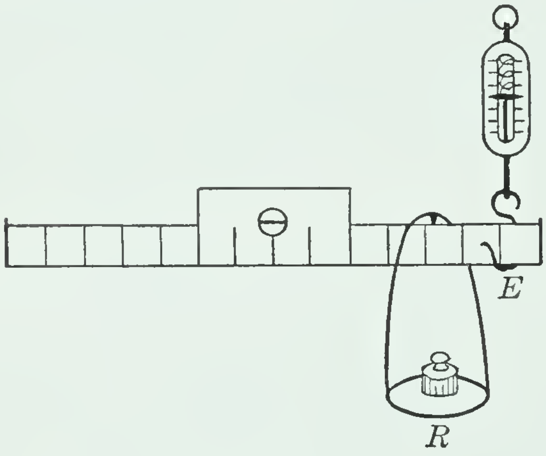


Fig. 4

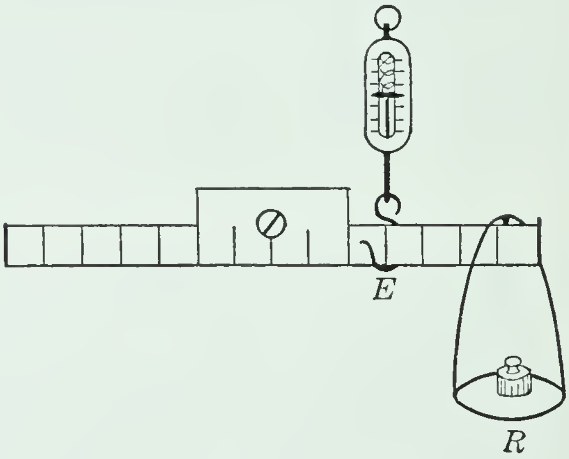


Fig. 5

3. *Third-class.* Place the scale pan with a 50-gm. weight in it, 12 cm. from the fulcrum. Hook the spring balance at E, 6 cm. from the fulcrum, and pull up until the lever is horizontal. See Figure 5. Record all data, and make computations just as you did with the first-class lever. Another trial, using different weights at different positions, should be taken.

Data: *Copy the table; do not mark your book.*

Class	Trial	E	R	D_e	D_r	$E \times D_e$	$R \times D_r$	Difference	R/E	D_e/D_r	Difference
First	1										
	2										
Second	3										
	4										
Third	5										
	6										

Questions:

1. What conditions are necessary to secure equilibrium?
2. Why is a moment error of 200 not a large error?
3. How may the mechanical advantage of any lever be found?
4. Why must the mechanical advantage of the second-class lever always be more than unity?
5. Why must the mechanical advantage of the third-class lever always be less than unity?
6. What can you say of the mechanical advantage of the first-class lever?

Experiment 4

PULLEY SYSTEMS

Purpose: (*a*) To find how to determine the mechanical advantage of pulleys and pulley systems; and (*b*) to find the efficiency of the pulley.

Apparatus: Two single pulleys; two pulleys with two sheaves each; meter stick; spring balance 250 gm.; set of weights; strong twine.

Background: The single fixed pulley is used for raising flags, awnings, windows, and other light objects. A combination of fixed and movable pulleys is used in the country for putting hay up in the mow. In the city, a system of pulleys (block and tackle) forms part of the mover's equipment; it is used to hoist or lower pianos, safes, and other heavy articles of furniture. The painter's scaffold is raised and lowered by a system of fixed and movable pulleys.

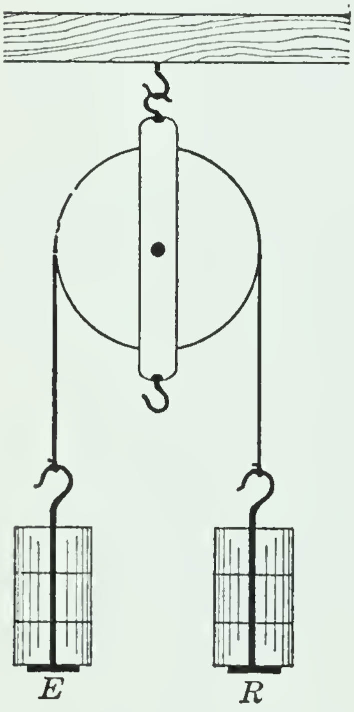


Fig. 6

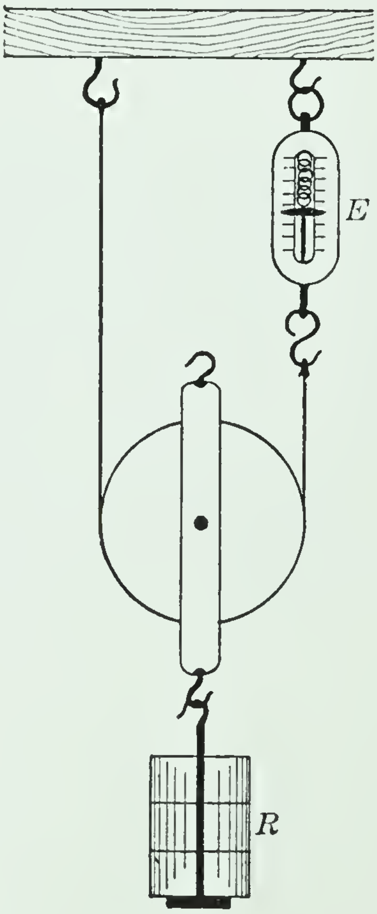


Fig. 7

Procedure:

1. *Single fixed pulley.* Arrange the fixed pulley as shown in Figure 6. A weight of 300 gm. is placed on the hanger R, and enough weights added to hanger E to pull R up very slowly. Record the total weight (300 gm. plus weight of hanger) in column R; the total weight required to raise the hanger R is recorded as $E + f$. This weight represents the effort spent in lifting the weight

and in overcoming friction. Next use just enough weights to let R move down slowly. The total weight (hanger included) at E is now $E - f$, or effort reduced by friction. The average of $E + f$ and $E - f$ is the actual effort E, since by this average we eliminate friction.

Stand a meter stick vertically between E and R. Read the position of both, and then pull E down through 20 cm., and see how much R has been raised in the meantime. Divide the resistance R by the effort E to find the mechanical advantage. Carry two decimal places. Find the mechanical advantage by dividing D_e by D_r, and get the difference between the two quotients.

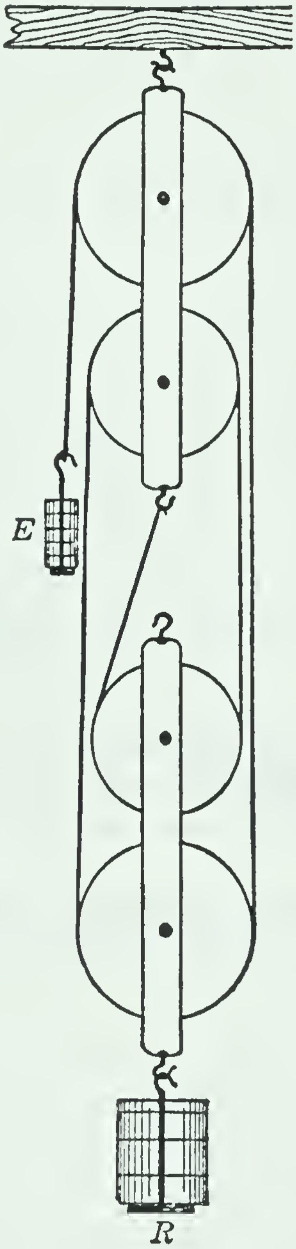


FIG. 8

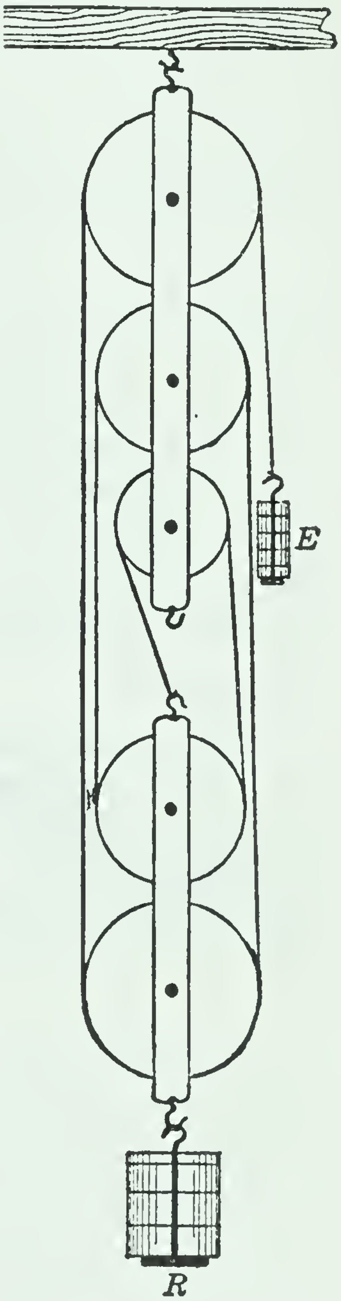


FIG. 9

2. *Single movable pulley.* Arrange the apparatus as shown in Figure 7. The resistance includes weight of hanger and weight of movable pulley. Use a spring balance to find the weight of the pulley and also to find the value of $E + f$ and $E - f$. The distances D_e and D_r may be found by the same method used with the fixed pulley. Compute the mechanical advantage.

NOTE: Considerable time will be saved if the instructor performs the remaining parts of the experiment in the presence of the class as a group. The result is more satisfactory, and less apparatus is required.

3. *Combination of pulleys.* (*a*) Weigh the movable pulley. Arrange the apparatus as shown in Figure 8, and proceed to find $E + f$, $E - f$, D_e, and D_r just as with the single fixed pulley. The weight on the hanger should be about 800 gm. to give the best results.

(*b*) The resistance R includes the weight of the hanger, movable pulley, and the added weights. Arrange the combination so the end of the cord will be attached to the fixed block as in Figure 9. Secure all the data just as in the preceding cases.

DATA: *Copy the table; do not mark your book.*

Arrangement	$E+f$	$E-f$	E	R	D_e	D_r	R/E	D_e/D_r	Difference	Theoretical MA	Efficiency

Efficiency. Find the useful work done by multiplying R by D_r; the total work done is found by multiplying $(E+f)$ by D_e. The efficiency equals $\frac{\text{useful work}}{\text{total work}}$ or $\frac{R \times D_r}{(E+f) \times D_e}$. Carry two places and record the efficiency in per cent. In the case of the movable pulleys, the resistance to be used should not include their weight. Why?

QUESTIONS:

1. What is gained by the use of the single fixed pulley?

2. In one combination the cord was fastened to the fixed block, and in the other combination to the movable block. How was the mechanical advantage affected?

3. Diagram a system of pulleys having a mechanical advantage of three.

Experiment 5

INCLINED PLANE

Purpose: (*a*) To learn how the mechanical advantage of an inclined plane is determined; and (*b*) to learn how much work is done in pulling a loaded car up an incline.

Apparatus: Inclined plane apparatus (a board 6 in. wide and 4 ft. long may be used); clamp; car, or roller; weights; spring balance, 2000 gm.; meter stick; strong twine.

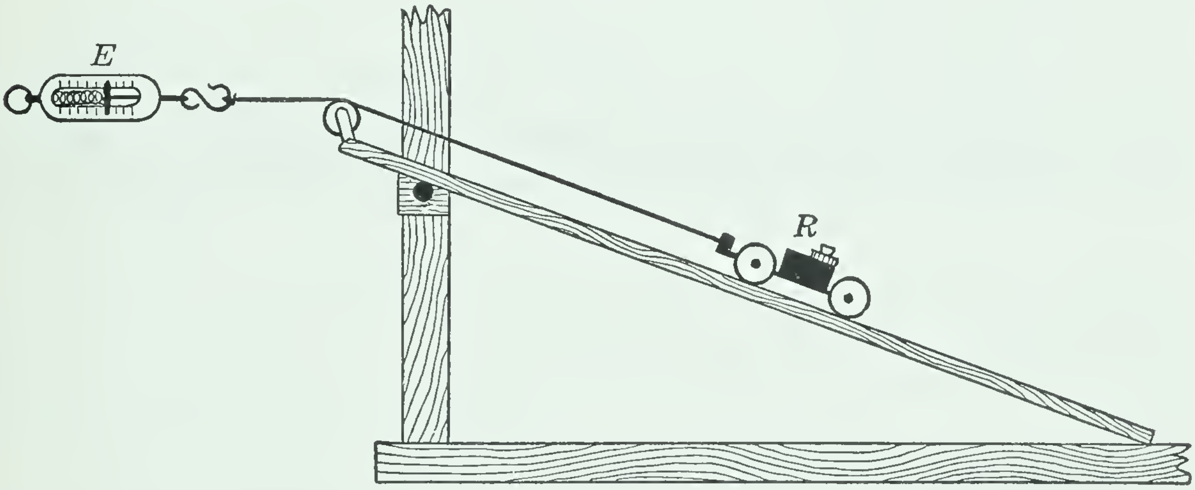


Fig. 10

Background: The gangplank to a boat, and a plank used to load heavy objects on a truck or wagon, are common examples of the inclined plane. An ordinary road up a hill is an inclined plane. The Egyptians are supposed to have used the inclined plane in building the great pyramids. Generally the effort is applied parallel to the plane and travels the whole length of the plane. It is the purpose of this experiment to learn what fractional part of the resistance must be used to keep the load moving when the length and height of the plane are known.

Procedure:

1. Support the plane as shown in Figure 10. Weigh the car and add to it a 500-gm. weight, calling the total resistance *R*. By the use of the

spring balance the force required to pull the car and weight slowly up the plane may be found. This force is to be recorded as $E + f$, or effort plus friction. A second reading taken as the car moves slowly down the plane is recorded as $E - f$, or effort reduced by friction. The average of $E + f$ and $E - f$ is the true effort E.

2. With a meter stick measure off along the lower edge of the plane just 100 cm. from the point of contact with the table, and mark the distance on the edge of the plane. Then measure the vertical height of the plane at the 100-cm. mark. If a regular inclined plane apparatus is used, the length and height may be read directly from the scales along the edges of the apparatus.

3. Find the mechanical advantage by dividing the length of the plane by its height. The mechanical advantage may also be found by dividing the resistance by the effort. Carry to two decimal places and find the difference.

4. Two more trials should be taken, using the same method as before, but changing the angle of the plane for each trial.

DATA: *Copy the table; do not mark your book.*

Trial	$E + f$	$E - f$	E	R	Length	Height	R/E	L/H	Difference	Work $= E \times L$
1										
2										
3										

PROBLEMS:

1. What force is needed to move a 1000-lb. wagon up a 4% grade (rising 4 ft. in 100 ft. of its length), if the efficiency is 80%? (Length is measured horizontally along the base.)

2. A plane is 20 ft. long and its height is 5 ft. What is the maximum load that a boy who exerts a force of 125 lb. can roll up the plane?

Experiment 6

SURFACE FILMS

Purpose: (*a*) To find some evidences of surface films on a liquid; and (*b*) to learn whether surface films are under tension.

Apparatus: Needle; razor blade; shallow dish or pan; 50 cc. graduated cylinder; match sticks; wire, 2 glass plates about 10 cm. × 15 cm.; glass funnel; soap solution; denatured alcohol; lubricating oil.

Procedure:

1. Place a razor blade on the surface of some water in a dish. As the blade floats note the shape of the surface of the water around the edges of the blade. Repeat, using a needle. It is necessary that metal objects be thoroughly dry and slightly oily in order that they may not be wet by the water.
2. Fill a 50 cc. graduate two-thirds full of water; then cautiously pour about 10 cc. of alcohol on top of the water so that the two liquids do not mix. Drop one or two drops of oil into the alcohol layer. (See Fig. 6–19.) Note the shape of the oil droplet.
3. Dip a wire ring containing a loop of thread into a dish of soap solution. (See Fig. 6–16.) Heat the end of a wire and touch it against a portion of the soap film which is inside the loop of thread. Note the result.
4. Wet the inside of a clean glass funnel and lower it, funnel down, into the soap solution. Remove it from the solution and note the behavior of the soap film formed across its diameter.
5. Float two match sticks on the surface of some pure water. Drop one drop of soap solution between the two sticks and notice their behavior. Repeat, using a drop of alcohol instead of soap.
6. Place a heavy rubber band over the vertical edges of two clean glass plates so that they are held firmly together. Place a piece of paper, as a wedge, between the opposite vertical sides; then lower the two plates into some water. Notice the shape which the water takes as it rises between the plates.

QUESTIONS:

1. Why do the razor blade and needle float in spite of the fact that they are more dense than water?
2. For a given volume of substances what geometric shape has the smallest surface area? Account for the shape which the oil drop assumed.
3. What evidence have we that surface films are under tension?
4. How may surface tension be weakened or lowered?

Experiment 7

SOLUTION AND EMULSION

Purpose: (*a*) To learn what conditions affect the solubility of solids and gases; and (*b*) what an emulsion is.

Apparatus: Small beakers; mortar and pestle; Erlenmeyer flasks; wire gauge; ring stand; burner; thermometer; funnel; test tube.

Material: Sodium chloride; potassium nitrate, crystals; sodium sulfate, crystals; ammonium hydroxide; hypo crystals; litmus paper; oil; soap solution.

Suggestion: Two students should work together in this experiment. Where potassium nitrate is used, all the solutions should be poured into a large bottle to prevent waste. Two students may then be assigned to recover the crystals by evaporating the solution in a casserole or large dish. The crystals may be dried and saved for further use.

Background: Some solids, such as salt and sugar, dissolve readily in water. Others are less soluble. The purpose of this experiment is to determine the factors that affect the solubilities of solids and gases. Water is our most useful solvent, but certain solids which do not dissolve readily in water may be dissolved in some other solvent. Some gases are only slightly soluble, others are moderately soluble, and a few gases are extremely soluble.

Procedure:

1. *Solids* (*a*) Weigh out two 5-gm. portions of *coarse* crystals of potassium nitrate. Grind one portion to a powder. Have at hand two beakers, each containing 25 cc. of water at room temperature. As one student adds the powdered potassium nitrate to one beaker, the other should add the crystal to the second beaker. Each should stir gently and observe the time required for complete solution in each case. *Pour the solutions into a large jar or bottle designated by the instructor.*

2. Repeat the experiment, but pulverize both portions. Stir one portion into the beaker of water as before, but let the other stand without agitation. Compare the rate at which solution occurs. Pour the solutions into the designated container.

3. Repeat (*a*), using two 5-gm. portions of large crystals. Compare the rate of solution, in one case using 25 cc. of water at room temperature, and in the other case 25 cc. of water at 60° C. Stir both all the time. Pour the solutions into the designated container.

4. Weigh out 5 gm. of sodium chloride. To 12 cc. of water in an Erlenmeyer flask, add this salt gradually, a little at a time, until no more will dissolve. Shake the flask after each addition of the salt. Heat the solution to 60° C., and again add salt until no more will dissolve. Let the solution cool, and observe.

5. Weigh out 15 gm. of potassium nitrate. Grind the crystals in a mortar, and add them, a little at a time, to 12 cc. of water in an Erlenmeyer flask. When the solution is *saturated* at room temperature, heat it to 60° C., and continue to add the potassium nitrate until no more will dissolve. Let the solution cool. Dry the crystals that are formed and return them to the instructor. Pour the mother liquor into a bottle or jar as designated by the instructor.

6. *Gases.* Warm rather gently one-half test tube of tap water. Record your observations.

7. Fill a test tube one-fourth full of ammonium hydroxide and heat it to the boiling point. Hold a piece of moist red litmus paper in the gas that escapes from the mouth of the tube.

INSTRUCTOR'S EXPERIMENT: *Supersaturation.* After 50 gm. of crystallized sodium sulfate have been dissolved in 25 cc. of water at 32° C., the solution should be filtered into a clean flask. The flask should be stoppered with a loose plug of cotton. When it has cooled to room temperature drop a crystal of sodium sulfate into the supersaturated solution. Note the change that occurs and observe the temperature change. The supersaturated solution may be prepared by dissolving 50 gm. of sodium thiosulfate (hypo) crystals in 10 cc. of water at 70° C.

8. *Emulsion.* To a test tube half-full of water add a few drops of oil and shake the tube vigorously. Allow the tube to stand for a short time; then note the change. Then add eight or ten drops of soap solution and again shake the tube. Compare the results in these two cases. Two liquids which do not mix are said to be *immiscible.* Any substance which makes oil remain suspended in water is known as an emulsifying agent.

QUESTIONS:

1. Make a list of three factors which affect the solubility of solids and state what effect each factor has.
2. How does temperature affect the solubility of a gas?
3. Define emulsion and give some illustrations.

Experiment 8

HYDROMETER AND SPECIFIC-GRAVITY BOTTLE

Purpose: (*a*) To determine the specific weight (or specific gravity) of a liquid by the specific-weight bottle; and (*b*) to determine the specific weight of a liquid by the hydrometer method.

Apparatus: *Bottle method.* Pycnometer; trip balance; set of weights; distilled water; alcohol; saturated solution of salt; solution of copper sulfate. Other liquids may be substituted or added.

Hydrometer method. Weighted rods, 30 cm. long and 1 sq. cm. cross-section; hydrometer jars, 12 in.; hydrometer, for light liquids; hydrometer, for heavy liquids; solutions as listed under first method.

Background: Several methods are in general use for finding the specific weights of liquids. By finding the weight of 100 cc. of salt water, and dividing it by the weight of the same volume of pure water, we find the specific weight of the salt water directly. This is known as the *flask* (pycnometer), or *bottle* method. One floats more easily in salt water than in fresh water, because the salt water is heavier and has more buoyancy. If a stick floating vertically (hydrometer) in salt water is transferred to fresh water, it will sink farther in the latter. The depths to which the stick sinks in any two liquids are inversely proportional to the specific weights of the liquids.

1. *Bottle method.* Weigh the *dry* specific-weight bottle. (See Fig. 11.) Fill it with distilled water, wipe off all the water from the outside, and weigh again. After the water has been poured out, the bottle should be rinsed two or three times with the liquid of unknown specific weight, then filled with the liquid, and weighed. Be sure to subtract the weight of the empty flask from the weight of the water and flask, and from the weight of the liquid of unknown density and the flask. Find the specific weight of the unknown liquid by dividing its weight by the weight of the water. (Equal volumes.) Proceed in the same manner, if other liquids are to be used.

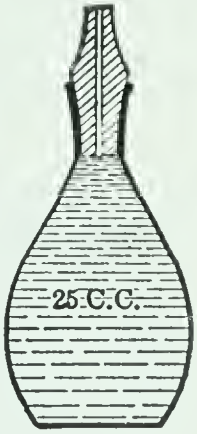


Fig. 11

DATA: *Copy the table; do not mark your book.*

Liquid	Weight of flask	Wt. of flask and water	Wt. of flask and liquid	Wt. of water	Wt. of liquid	Specific weight

2. *Hydrometer method.* Put the hydrometer rod, weighted end down, into the jar of water, and read the number of centimeters submerged. (See Fig. 12.) Remove the rod, wipe it dry, and put it into the jar containing the liquid of unknown specific weight. The sp. wt. equals the number of centimeters submerged in water divided by the number of centimeters submerged in the x liquid. Proceed in the same manner to find the specific weight of such liquids as the instructor directs. Use a *commercial* hydrometer to find the specific weight of each liquid used. (See Fig. 13.)

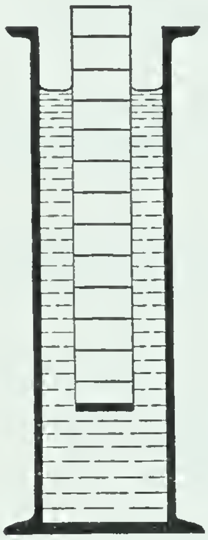


FIG. 12

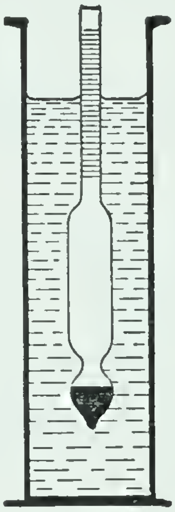


FIG. 13

DATA: *Copy the table; do not mark your book.*

Liquid	Length (L) of rod submerged in water	Length (L') of rod submerged in x liquid	Specific weight L/L'	Specific weight, by hydrometer

PROBLEMS:

1. If a lactometer is available, test a sample of milk. The New York Board of Health lactometer reads at least 100 in milk free from added water. After testing the milk, add a little water to it and test again. Record the readings.

2. Name as many practical applications of the specific weight of liquids as you can.

3. Examine the storage battery tester. What kind of specific weight instrument is it?

4. What kind of instrument does the mechanic use to determine the freezing point of an alcohol solution used as an antifreeze in the radiator of a car?

Experiment 9

EFFECTS OF AIR PRESSURE

Purpose: (*a*) To obtain some evidence that air exerts pressure; (*b*) to learn in what direction air exerts pressure; and (*c*) to learn how the volume of a given quantity of gas varies with pressure.

Apparatus: Drinking glass; cardboard; rectangular tin can; rubber stopper or screw cap to fit the tin can; 18-inch length of rubber tubing; ring stand; burette clamp; meter stick; barometer; glass tubing bent as directed; thistle tube, drawn to a point; medicine dropper; $\frac{1}{2}$ lb. mercury.

Background: At sea level the air pressure is 14.7 lb. per sq. in. By means of a compression pump, we can crowd 5 atmospheres, or 5 times as much air, into an automobile tire as it contained at atmospheric pressure. The pressure the air exerts against the walls of the tire is 73.5 lb. per sq. in. When the valve is opened, the air expands again to 5 times its original volume. All gases are perfectly elastic. The use of steel cylinders for storing such gases as oxygen, hydrogen, carbon dioxide, nitrogen, and ammonia is common. The gases are forced into the cylinder under a pressure of 10 atmospheres or more; they expand correspondingly when the valve is opened. The behavior of gases under varying pressure was studied by Robert Boyle, who formulated the law that bears his name.

Procedure:

1. Fill a drinking glass two-thirds full of water, press a smooth piece of cardboard over the mouth, invert the glass, and remove your hand. Note the result. Turn the glass sidewise. Note the result.
2. Place the end of a medicine dropper beneath the surface of some water and press the bulb. Note the escape of air. Release the pressure on the bulb. Note the rise of water in the tube.
3. Pour about 50 cc. of water into a rectangular tin can and heat it over a Bunsen flame until there is a flow of steam from the neck. Withdraw the flame and quickly close the neck with a screw cap or rubber stopper. Pour cold water on the can. Note the result.
4. Obtain a thick-walled glass tube $4\frac{1}{2}$ ft. long and not over $\frac{1}{4}$ in. internal diameter. (3/16 in. is better.) Draw it out at one end to make a

short jet tube which can be easily sealed. Eighteen inches from this end bend the tube at right angles. Make another right angle bend 6 in. from the other end of the tube, but this bend should be at right angles to the plane formed by the first bend. (See Fig. 14.) This gives us a tube with one end turned up as the L-shaped portion of the tube lies flat on the table. While the end *D* is raised a few inches, enough mercury should be added (use the thistle tube) at *C* to fill *AB*, and about 1 in. of *AD*. Next seal *D* so it is airtight. As the tube lies on the table, we have a cylindrical column of air enclosed in *AD* under a pressure equal to that of the atmosphere. Measure the length of the air column in centimeters and record it as the original volume. The volume of a cylinder is proportional to its length. The barometer reading (in cm.) is the original pressure.

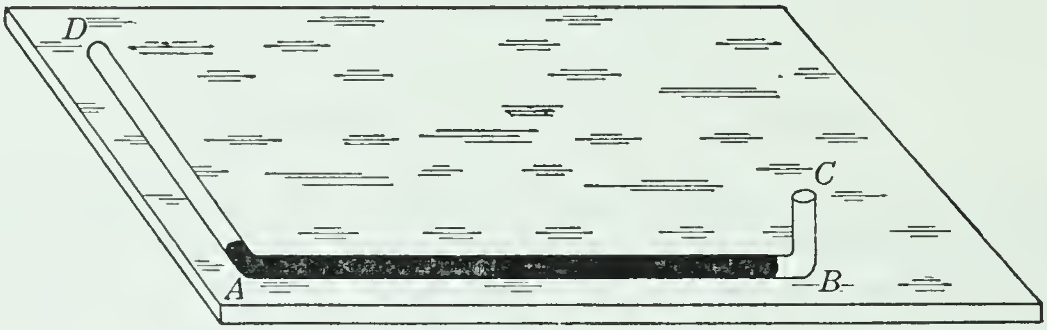


Fig. 14

5. While *AD* is kept flat on the table, lift the end *B* 15 or 20 cm., and clamp the tube firmly in position. This rotates the tube about *AD* as an axis. Measure the length of the air column to find the new volume. Measure the vertical height of the end of the mercury column in *AB*. Since the pressure upon the air has been increased by the vertical height of the mercury, we must add this reading to the barometer reading each time to find the new pressure.

6. Take at least four more readings, lifting the tube at *B* enough each time so the pressure will be increased by 12 or 15 cm. For the last reading the tube *AB* may be held vertically.

7. Since the volume decreases as the pressure increases, the product of the pressure and volume should be the same in all cases. Stated algebraically, VP = a constant. Calculate the product VP for all cases. The common J-tube may be used in this experiment if the instructor so directs.

DATA: *Copy the table; do not mark your book.*

Trial	Length of air column, V	Height of mercury	Total pressure of mercury (cm.) P	$P \times V$
1				
2				
3				
4				
5				
6				

QUESTIONS:

1. What holds the cardboard on the glass in step 1? What is the purpose of the cardboard?
2. What causes water to rise in the medicine dropper? Explain.
3. What was the object of boiling the water in the tin can in step 3? What happened to the can? Explain.
4. In what directions is air pressure exerted? Use observations in this experiment to confirm your answer.
5. How do the different values for $P \times V$ compare in step 4? State Boyle's law.

PROBLEMS:

1. The volume of a dry gas is 640 cc. when the barometer reads 78 cm. What will its volume be when the pressure upon it is 90 cm. of mercury?
2. The volume of dry gas is 230 cc. when the pressure upon it is 70 cm. What pressure must be applied to this gas to reduce its volume to 100 cc.?
3. Plot a curve, using the volumes as abscissas and the pressures as ordinates.

Experiment 10

PARALLELOGRAM OF FORCE

Purpose: (*a*) To find, when two forces act at an angle on a point, what must be the magnitude and direction of a third force which produces equilibrium; and (*b*) to learn how the third force compares with the resultant of the first two forces.

Apparatus: Three spring balances, 2000 gm. capacity; wooden block; strong twine; small iron ring, $\frac{1}{2}$ in. diameter; ruler; compasses; three iron clamps, or a board like that shown in Figure 15. (A pastry board, 18 × 24 in., or a drawing board is cheaper and more convenient than the clamps. Several holes may be bored in the board and pieces of $\frac{1}{4}$ in.

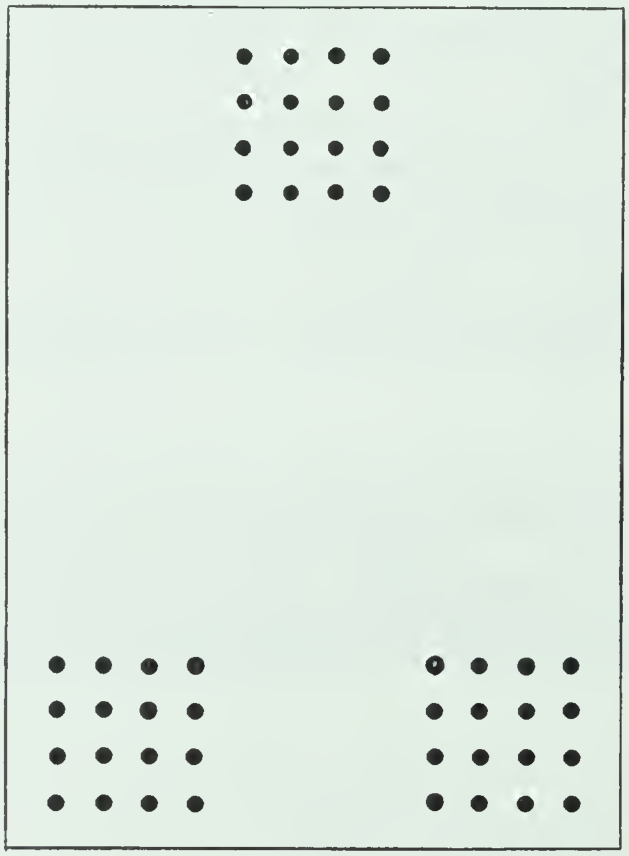


Fig. 15

dowel rod slipped through the rings of the balances to hold them in position.)

Background: A man rowing a boat across a stream is carried downstream by the current. Two boys kick a football; one kicks northerly, and the other westerly. The ball moves northwesterly. Very often two forces act upon a body at the same point. The angle between the forces may have any value from zero to 180°. The resultant of two or more forces is that single force which could be substituted for them without altering the effect. When the forces act at an angle, the resultant is equal to the diagonal of a parallelogram of which the two forces are sides. The equilibrant is a single force which produces equilibrium with two or more forces.

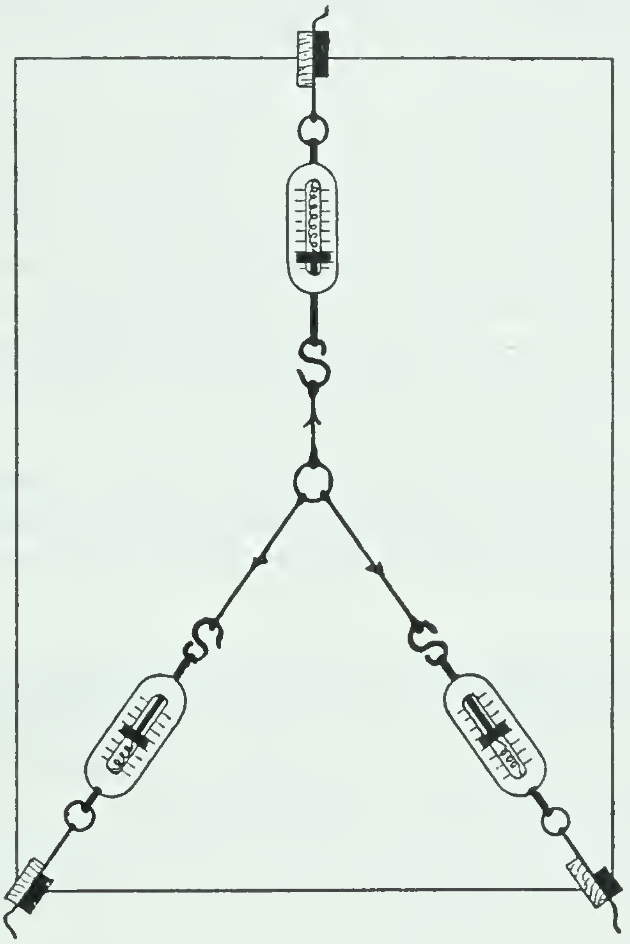


Fig. 16

Procedure:

1. Cut three pieces of twine about 10 in. long. Fasten one end of each piece to the small iron ring. In the other end make a loop to slip over the hook of the balance. (See Fig. 16.) Fasten the balances to clamps along the edges of the table so the tension on all the balances will be approximately the same. They should not vary more than 200 or 300 gm.,

and no balance should read less than 1000 gm. Adjust the cords on the rings so the pull of each balance is in direct line with the center of the ring.

2. Place a blank sheet of paper on the board or table so its center will be directly beneath the center of the ring. It is a good plan to stick a couple of pins in opposite corners of the paper to keep it from slipping while the experiment is being performed. Place a wooden block on the paper so that its edge just touches one of the strings, but does not displace it. Using a *fine-pointed* pencil, draw a line along the edge of the block, just under the string. In the same manner, mark the direction of the other strings. Read each balance, and record its magnitude at the end of the line which represents the direction of the force.

3. Remove the paper and produce the lines until they meet. If the work was carefully done, the lines will all meet at the same point. Consider this the point of application of the three forces. The lines drawn show the direction of the forces, and the balance readings their magnitude.

4. Select a convenient unit (1 cm. to represent 200 or 250 gm.), and measure off on each line the distance needed to represent the balance reading. Using any two of the forces thus represented graphically as sides, construct a parallelogram. Draw its diagonal and find its magnitude in terms of the scale used. How does it compare with the third force in magnitude and direction? What is it called? What is the third force called?

5. If the instructor so directs, complete parallelograms with the other forces as sides, and draw their diagonals. It is a good plan to represent the forces by solid lines, and use dotted lines for the construction lines.

PROBLEMS:

1. What are the chief sources of error in this experiment?

2. Represent graphically a force of 30 lb. acting easterly upon a given point, and a force of 50 lb. acting southerly. Compute the resultant and show the equilibrant. (Let $\frac{1}{2}$ in. represent 10 lb.)

Experiment 11

SOURCES OF HEAT

Purpose: To learn the general sources of heat.

Apparatus: Hand drill and bit; strip of iron about $\frac{1}{8}$ in. thick; bicycle or automobile pump; candle; alcohol; evaporating dish; electric light; two thermometers; piece of ice.

Procedure:

1. With a hand drill and bit, drill a hole in a strip of $\frac{1}{8}$ in. iron. Feel of the iron and bit. Note any change in temperature. Rub two pieces of ice together. Is there any evidence that heat is formed?
2. Close the end of the tube of a bicycle or automobile pump with your finger and pump fifteen or twenty strokes as rapidly as possible. Feel of the bottom of the pump barrel and of the tube. Note any change in temperature.
3. Light a candle. Note the heat produced. Light some alcohol in an evaporating dish. Note whether heat is produced.
4. Turn on an electric light. Hold your hand near the bulb. Is heat produced?
5. Place a thermometer in the sunshine. Place a second thermometer near the first but in the shade. Note the temperature of each after ten minutes.

Questions:

1. Each of the five steps in this experiment represents a general method of producing or obtaining heat. Name the general method which each step represents.
2. What is the source of all heat?

Experiment 12

EXPANSION DUE TO HEAT

Purpose: To find out, when the temperature of a metal rod is increased one degree Centigrade, how much it expands.

Apparatus: Steam boiler; burner; meter stick; and apparatus as shown in Figures 17 and 18; 60 cm. rods of aluminum and brass.

Background: In this method of finding the coefficient of linear expansion, one end of the rod is fixed, and the other acts against the short arm of a bent lever. Thus a small increase in length is multiplied by the lever so that it may be read more accurately.

Procedure:

1. Remove the rod and steam jacket from the frame in Figure 17. Stand them on end on the table and measure with a meter stick the length of the rod in millimeters. Replace the rod and steam-jacket and fasten them by the set-screw *S*. Remove the bent lever and measure the arms *AB* and *BC*. (See Fig. 18.) Measure the short arm from the center of the hole to the point where it rests against the end of the rod. The long arm should be measured from the center of the hole to its tip end. After you have replaced the lever, so adjust the thumb-screw *T* that the end *C* of the lever will just coincide with the *zero* of the scale. Read

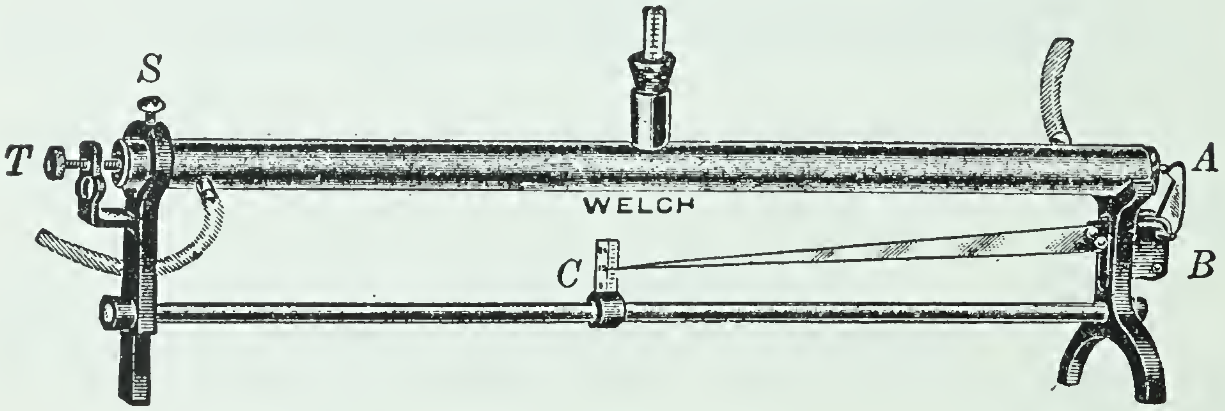


Fig. 17

the thermometer and then pass steam through the jacket for at least three minutes. When the end C ceases to move, read the number of millimeters through which it has moved, and also read the thermometer again.

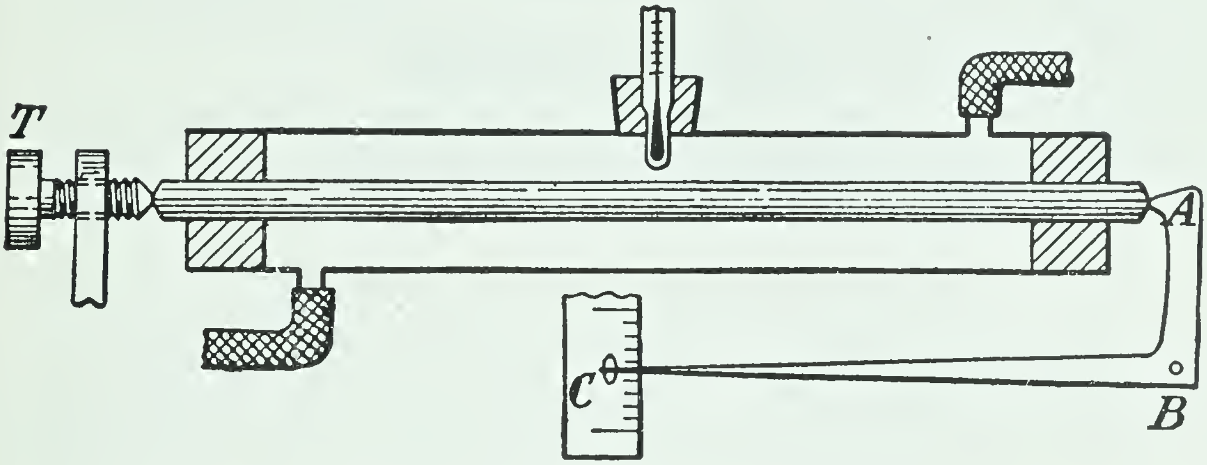


Fig. 18

2. The movement of the end of the lever C does not show the true increase in the length of the rod. To find the increase we must first find the ratio of the length of the two arms of the lever by dividing the length of the long arm by that of the short arm. (Carry three decimal places.) Then divide the number of millimeters that the end of the lever moves by the above ratio. This figure gives the total increase in length of the rod. We find the change of temperature and then calculate the increase in the length of the whole rod for one degree change in temperature. Next we calculate the increase per unit length (one mm.) for one degree Centigrade.

Data:

1. What is the length of the rod?
2. What is the length of the long arm of lever, BC?
3. What is the length of the short arm of lever, AB?
4. What is the ratio of lengths of two arms ($BC \div AB$)?
5. What is the temperature of rod at the beginning?
6. What is the temperature of rod at the end?
7. What is the change in temperature?
8. What is the number of millimeters that tip C moves?
9. What is the total increase in the length of the rod? (No. 8 ÷ No. 4)
10. What is the expansion of the entire rod per degree?
11. What is the expansion of one mm. per degree Centigrade?
12. What is the accepted value in each case? (See Table 7 in Appendix A.)
13. What is the per cent of error?

PROBLEMS:

1. One end of a steel bridge is often supported on rollers. Explain.
2. A steel wire is 1000 ft. long at 0° C. Find its length at 60° C. (Coefficient of expansion of steel, 0.000013 per degree Centigrade.)
3. Mention three cases where the expansion and contraction of a metal because of temperature changes is a disadvantage.
4. What are two cases where man makes uses of the expansion and contraction of a metal during a temperature change?

Experiment 13

CALIBRATING A THERMOMETER

Purpose: To find out how a thermometer scale is made.

Apparatus: 250-cc. beaker; uncalibrated thermometer; cracked ice; steam generator; Bunsen burner; metric ruler; glass-marking pencil; triangular file; rubber stopper to fit steam-generator chimney; barometer (mercury).

Procedure:

1. *Freezing point.* Fill a 250-cc. beaker with finely chopped ice and pour over it enough water to fill the space between the pieces of ice. Put the uncalibrated thermometer bulb down into the ice and allow it to remain for about 15 minutes. (While waiting for the thermometer to reach the temperature of the melting ice start the water heating for step 2.) Lift the thermometer until the top of the mercury column is barely visible. With the sharp point of a glass-marking pencil carefully mark the level of the mercury. This represents the freezing point of water or 0° C. A small scratch with a triangular file should be made at the pencil mark in case the latter is destroyed in step 2.

2. *Boiling point.* Fill the steam generator about one-third full of water, screw on the chimney, and heat the water with a Bunsen burner. After the thermometer of step 1 has warmed to room temperature, slip it into the rubber stoppers and slowly lower it into the steam generator chimney (Fig. 9–18). The stopper should be adjusted so that when the mercury stops rising its level will be just above the top of the stopper. When the mercury stops rising mark the level with the pencil. This represents the boiling point of water and is 100° C. if the air pressure is 760 mm.

At atmospheric pressures above 760 mm. the boiling point of water is above 100° C. and at pressures below 760 mm. the boiling point is below 100° C. A change in pressure of 10 mm. causes a change in boiling point of approximately 0.37° C.

Reading a barometer. If the reading shows the pressure of the air to be within 15 mm. of 760, we may disregard the small error caused in the location of the boiling point. Mark the distance between the freezing-point mark and the boiling-point mark on a strip of paper. Divide the space between these two marks into 100 equal parts and number at 5-degree intervals; paste the edge of the scale on the thermometer. If the barometer reading is more than 15 mm. above or below 760 mm., calculate the true temperature at which water boils. This then represents the top-line temperature on the thermometer. For example, if the pressure is 733 mm. then the boiling point of water is $100 - (2.7 \times 0.37) = 99°$ C. The distance between the two marks on the thermometer would then be divided into 99 equal parts and extended upward 1 part to 100.

QUESTIONS:

1. Explain why the inside diameter of the thermometer tube must be uniform.

2. Why is it necessary to submerge as much of the length of the thermometer as possible in steam while determining the boiling point when only the lower portion of the tube is submerged in ice in determining the freezing point?

3. It is possible to estimate the altitude of a place with an accurate thermometer. Explain how this may be done.

4. How does the inside diameter of a thermometer tube affect its sensitivity?

5. The coefficient of cubical expansion of mercury is 0.00018 while that of alcohol is 0.0011. Which of the two liquids would make the more sensitive thermometer?

Experiment 14

TRANSFER OF HEAT IN CONDENSATION AND EVAPORATION

Purpose: To find out how many calories of heat are required to vaporize one gram of water without change of temperature.

Apparatus: Steam boiler, fitted with rubber tubing, a water trap, and piece of glass tubing 8 in. long; calorimeter; trip balance; set of weights; lumps of ice; thermometer; Bunsen burner.

Background: It does not take very long to warm a quart of water to the boiling point, but it takes more than five times as long to change it all into steam, or vapor. If we test the steam from time to time we find that its temperature is constant. All the time that the water is boiling away, it is absorbing heat. The heat required to vaporize one gram of water (without temperature change) is called the *heat of vaporization.* Since a thermometer does not show any evidence of heat absorption, heat of vaporization is often called *latent*, or hidden, heat. That heat is really present may be shown by passing the steam into cold water, and noting the rise in temperature. In this experiment, we shall pass a known weight of steam into a known weight of water, and then compute the number of calories yielded by the steam upon condensation. The heat lost upon condensation equals the heat absorbed during vaporization.

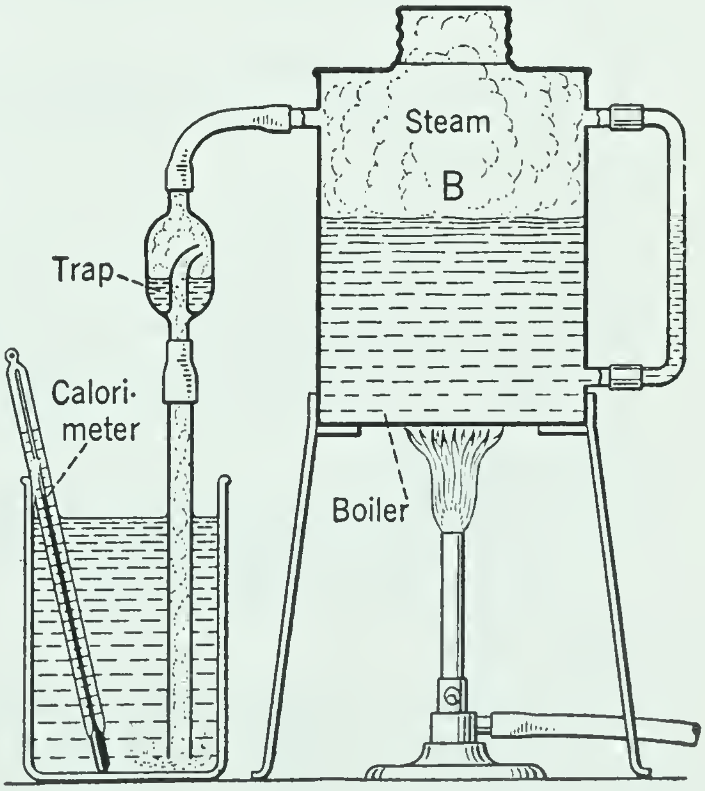


Fig. 19

Procedure:

1. Light the burner under the steam boiler, which should be fitted with a water trap as shown in Figure 19. While

the water is heating, weigh the calorimeter, fill it two-thirds full of water at about 5° C., and weigh again. Stir the water thoroughly with the thermometer, and take its temperature, estimating to tenths of a degree, *just* before the steam is introduced. Then pass a steady current of steam into the water until the temperature rises to about 35° C. Remove the glass tube, stir the water thoroughly, and take the temperature accurately. Weigh the calorimeter and contents; the increase in weight equals the weight of steam introduced. The temperature of the steam may be read directly from the steam boiler, or preferably, it may be computed from the barometer reading. (See Exp. 13.) In the calculations, the student must remember that the steam furnished heat upon condensing, and that an equal weight of water at 100° C. was formed. The water which is thus formed also furnishes heat in cooling to the final temperature.

DATA:

1. What is the weight of the calorimeter?
2. What is the specific heat of the calorimeter?
3. What is the weight of the water and the calorimeter?
4. What is the weight of the water?
5. What is the original temperature of the water and the calorimeter?
6. What is the temperature of the steam?
7. What is the final temperature of the water and the calorimeter?
8. What is the weight of the water, the calorimeter, and the added steam?
9. What is the weight of the steam?
10. How many calories are gained by the calorimeter? (wt. × temp. change × sp. ht.)
11. How many calories are gained by the water? (wt. × temp. change × sp. ht.)
12. What is the total number of calories gained?
13. How many calories are lost by the steam in condensing and cooling to the final temperature? (same as cal. gained)
14. How many calories are lost by hot water? (wt. of steam × [100 − final temp.] × 1)
15. How many calories are lost by x gm. of steam in condensing?
16. How many calories are lost by 1 gm. of steam during condensation?
17. What is the per cent of error?

QUESTIONS:

1. Why does the evaporation of perspiration produce a cooling effect?
2. Can steam be heated above 100° C.? Explain.
3. How many calories of heat are liberated when 50 gm. of steam condense, cool to zero, and freeze to ice at zero?

Experiment 15

LAWS OF BOILING

Purpose: To learn what factors affect the boiling point of a liquid.

Apparatus: Steam generator; manometer tube with mercury; Bunsen burner; thermometer; 2-in. length of rubber tubing; pinch clamp; distilling flask; condenser; rubber tubing for condenser; 500-cc. flask; 2 ring stands; 2 iron clamps; table salt; denatured alcohol; solid rubber stopper to fit the 500-cc. flask; beaker; vacuum pump.

Procedure:

1. Set up the steam generator as shown in Fig. 9–18. Slip a 2-in. length of rubber tubing on the outlet tube near the top of the chimney, press the stopper holding the thermometer firmly into the top of the chimney, and heat the water in the generator to boiling. Note the temperature while the water boils for a few minutes. Clamp the side of the chimney with a pinch clamp. (*Caution:* Leave the clamp on only for a short time in order that the steam pressure may not force the mercury out of the manometer tube or the stopper out of the top of the chimney.) Note the rise of the mercury in the manometer tube. Read the thermometer. Has the boiling point changed with the increase in pressure?

2. Fill the 500-cc. flask half full of water and heat it to boiling. Insert the solid rubber stopper, invert the flask as in Fig. 11–18, and pour cold water on it. Observe the water inside the flask. Fill a beaker half full of water at room temperature, insert a thermometer, and place the beaker and thermometer under the bell glass of a vacuum pump. Start the pump. After a few minutes observe the water and note the temperature. Does reduction of air pressure have any effect upon the boiling point of water?

3. Set up the apparatus as shown in Fig. 11–25. Dissolve about 30 gm. of table salt in 100 cc. of water, pour the solution into the distilling flask *A*, and heat until it has boiled a few minutes. Note the temperature. How does the boiling point of salt solution compare with that of pure water as determined in step 1? Taste the distillate in *B*. Does it contain salt?

Replace the salt solution in *A* with a solution of 25 cc. of alcohol in 25 cc. of water and boil it for a few minutes. Note the boiling temperature. How does this temperature compare with that of pure water and with that of salt solution? Smell of the distillate in *B*. Is it pure water?

QUESTIONS:

1. Does the temperature change while boiling a pure liquid, provided there is no change in pressure?
2. Is the boiling point of a pure liquid always the same at a given pressure?
3. How does change in pressure affect the boiling point of a liquid?
4. How do dissolved solids affect the boiling point of a liquid? Of dissolved liquids?
5. Summarize the above questions and answers into four statements called the laws of boiling.

Experiment 16

TRANSMISSION OF HEAT

Purpose: To find how heat may be transmitted from one place to another.

Apparatus: Flask, 250 cc.; two-holed rubber stopper to fit flask; glass tubing; burner; ring stand or tripod; potassium permanganate solution, $\frac{1}{2}\%$; battery jar, 8 in. or 10 in.; bright metal cup; a second cup, same material as first, but coated on the outside with lampblack; two thermometers; two beakers, 250 cc.; one beaker, 1000 cc.; ring stand; wire gauze; burner; thermos bottle; watch.

Background: Convection is one of the most important methods of distributing heat. It occurs only in liquids and gases. The general principle of convection depends upon the fact that both liquids and gases expand when heated. When such expansion occurs, the density is correspondingly diminished. If unequal heating occurs, that portion of the liquid or gas which is more highly heated expands and becomes less dense. It is then pushed upward by the heavier, colder liquid or gas which surrounds it. Thus convection currents are produced. Warm or hot objects radiate heat to the surrounding medium. The rate at which heat is radiated depends upon the color of the radiator and upon the nature of its surface. How do the outside walls of the cylinders of a motorcycle compare with those of the cylinders of the automobile? Explain. Good absorbers of heat, such as rough, dark surfaces, are also good radiators. Some substances serve as heat insulators. They do not conduct the heat to the surface readily, hence it cannot be radiated to the surrounding medium. A vacuum is the best heat insulator.

Procedure:

1. Fill the small flask nearly to the top with the potassium permanganate solution, and then heat the solution to about 60° C. See whether you observe any expansion during the heating. Close the flask with the rubber stopper, which carries two pieces of glass tubing, one extending almost to the bottom of the flask and the other long enough to reach almost to the surface of the water in a large battery jar when the flask

rests on the bottom of the jar as shown in Figure 20. Lower the flask into the battery jar, which should be almost full of water. Make a sketch diagram of the apparatus and the convection currents which are set up.

2. Fill the large beaker with water and heat it to about 80° C. With this hot water fill each of the 250-cc. beakers and transfer it quickly to the metal cups, 250 cc. in each cup. One student should take thermometer readings for the polished cup at two-minute intervals while a second student takes readings for the blackened cup. Both should continue in this manner until 6 or 8 readings have been taken. The temperature of the room should also be recorded.

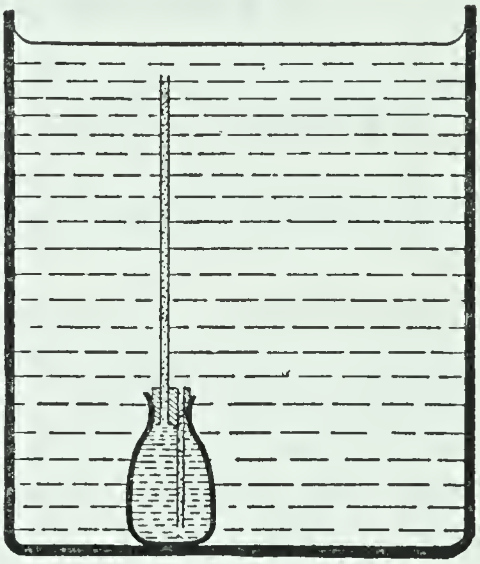


Fig. 20

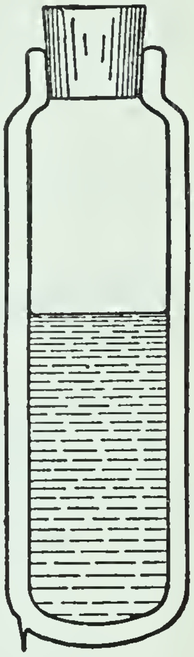


Fig. 21

If a thermos bottle is available, the instructor may pour 250 cc. of the hot water into the thermos bottle and let a student take thermometer readings at 10-min. intervals throughout the laboratory period. (See Fig. 21.)

Data: *Copy the table; do not mark your book.*

Time	Temperature of polished cup	Temperature of blackened cup	Temp. of polished cup — room temperature	Temp. of blackened cup — room temperature

1. What is the temperature of the room?
2. What is the temperature of the water in the thermos bottle on each of the trials?

Questions:

1. At the beginning of step 1, how was the heat transmitted from the flame to the water in the flask?

2. Make a list of practical applications of convection currents.

3. Why do the outside walls of motorcycle cylinders and air-cooled airplane-engine cylinders have fins? Rate of cooling is directly proportional to what?

4. From a consideration of your experiment, should steam radiators be highly polished? Should they be black? Explain.

5. Name the three general methods of heat transfer.

Experiment 17

PHYSICAL AND CHEMICAL CHANGES

PURPOSE: To learn the difference between a chemical and a physical change.

APPARATUS: Burner; tweezers; test tubes; watch glass; beaker; asbestos board; mortar and pestle; sandpaper; magnesium ribbon; copper wire, or copper foil; zinc; sulfuric acid, 1 to 6; solution of silver nitrate, 2%; hydrochloric acid, 1 to 4; platinum wire, sealed in glass rod; sodium chloride crystals (table salt).

BACKGROUND: The amount of matter in the world does not vary, but matter is undergoing many changes. In some cases only the form or state is changed. Ice melts or water evaporates. Such changes are *physical.* In other cases the substance loses its identity and acquires new characteristic properties. Wood burns and metals tarnish. Such changes are *chemical.* Heat, light, electricity, and solution are often instrumental in starting chemical changes. In many cases, too, they are the immediate result of such changes.

PROCEDURE:

1. Examine a piece of platinum wire. Note its color and luster. Then hold the wire in the flame of your burner for a couple of minutes. Examine the wire, after it has been allowed to cool.

2. Sandpaper a piece of magnesium ribbon and note its color, luster, and flexibility. Holding one end with the tweezers, thrust the other end into the flame. The ash, which may be collected on a piece of asbestos board, should be compared with the magnesium ribbon.

3. Sandpaper a piece of copper wire and examine it carefully. Hold the wire in the outer cone of the flame for a few minutes. Repeat the examination. Scrape off some of the scale which forms and compare it with the copper wire. Heat the wire a second time and again scrape off the scale, which may be collected on a piece of paper. Repeat once more.

4. Dip your platinum wire into a test tube containing 4 or 5 cc. of dilute sulfuric acid. Watch carefully for any signs of chemical action. Remove the wire and add a small piece of zinc to the acid. Let the action continue for five minutes, warming the tube if the action starts slowly.

Remove any undissolved zinc, and evaporate the liquid that is left by pouring it on a watch glass which rests on the rim of a beaker one third full of water. Boil the water in the beaker until about 80% of the liquid on the watch glass is evaporated. Compare the crystals that form with the original zinc and with the acid.

5. To two or three cc. of silver nitrate solution add a few drops of hydrochloric acid. The white, curdy solid that separates from the solution is called a *precipitate*. Pour the contents of the tube upon a folded filter. The part that flows through the paper is called the *filtrate*. Unfold the filter and expose the precipitate on the filter to direct sunlight for a short time.

6. Taste some sodium chloride crystals. Pulverize some of the crystals with a mortar and pestle and taste the powder. Dissolve the powder in water and taste the solution. Evaporate the solution to dryness in a beaker over a Bunsen flame. Allow the solid residue to cool; then taste it. Compare the taste in each of the four cases.

QUESTIONS:

1. What type of change occurs when platinum is heated?

2. Is a new substance formed when magnesium is heated? Give a reason for your answer.

3. Is the scale that is formed when copper is heated still copper? Give a reason for your answer. Does this represent a chemical or a physical change?

4. Compare the action of sulfuric acid on platinum and zinc.

5. Does the precipitate formed in step 5 appear to be a new substance? What is the effect of sunlight on it?

6. In step 6, does pulverizing the crystals of salt represent a physical or a chemical change? Dissolving the salt involves what kind of change? What kind of change is evaporation or recrystallization?

7. Summarize the results of this experiment in a definite, concise statement of what a physical change is and what a chemical change is.

Experiment 18

PREPARATION AND STUDY OF OXYGEN

PURPOSE: To learn how to prepare oxygen; and to learn some of the chemical and physical properties of oxygen.

APPARATUS: Test tube, and one-hole rubber stopper to fit; four wide-mouthed bottles; four glass plates; burner; stand; deflagrating spoon; clamp; pneumatic trough; glass elbow; rubber delivery tube; oxygen mixture (2 parts potassium chlorate to 1 of manganese dioxide); sulfur; charcoal; magnesium ribbon; limewater; picture wire; red phosphorus.

SUGGESTION: The instructor should heat a small quantity of the oxygen mixture in an open dish to see that it is free from impurities that might cause a dangerous explosion. Considerable time will be saved in this experiment if the mixture is prepared by the instructor and the student directed to use about one-fourth test tube full. (30-cc. tube.) If the student weighs out his material, he may use 6 gm. of potassium chlorate and 3 gm. of manganese dioxide.

BACKGROUND: Many compounds contain an abundant supply of oxygen, but some of them, water and carbon dioxide for example, are so stable that they are not easily decomposed by heating. Potassium chlorate, however, contains oxygen, and it gives up all or part of its oxygen readily when heated. Thus it is suitable for use in preparing oxygen. Any such compound, rich in oxygen and quite unstable, might be used. Manganese dioxide accelerates the reaction, but it does not supply the oxygen.

PROCEDURE:

1. Clamp the test tube containing the oxygen mixture in a slightly inclined position and fit it with a stopper and delivery tube for collecting gas by water displacement as shown in Fig. 13–6. A bent glass tube may be used instead of the rubber tubing. Have four bottles (capacity about 300 cc.) filled with water and placed upside down in the pneumatic trough before beginning to heat the tube. Now heat the tube *gently*, beginning to heat at the top of the mixture. Keep the flame moving to heat all the lower end of the tube. Collect four bottles of oxygen gas.

Pure oxygen is colorless, the white fumes which often appear being due to impurities. *Do not forget to remove the delivery tube from the water as soon as the heat is withdrawn.*

2. Slip a glass plate under the mouth of one of the bottles, remove it from the trough, and stand it mouth upward on the table. Holding a piece of charcoal with the tweezers, heat it until it glows and then thrust it into the bottle of oxygen. Charcoal is nearly pure carbon. It unites with oxygen to form carbon dioxide. Test for this gas by pouring 15 cc. or more of limewater into the bottle, covering it with the hand and shaking it vigorously. The white precipitate is formed by the action of carbon dioxide on the limewater. This serves as a *test for carbon dioxide.*

3. Wrap one end of a bright piece of magnesium ribbon around the end of the tweezers. Hold it in the flame until it starts to burn and then thrust it *quickly* into a second bottle of oxygen. Compare the speed of combustion in air and in oxygen. Compare the products formed in each case. Burn a short piece in air for comparison.

4. Put a little sulfur (bulk of a *small* pea) in a deflagrating spoon, ignite it, and thrust it into a third bottle of oxygen. Note the odor of the gas (*cautiously*). Waft some of the gas toward the nostrils by passing the hand over the mouth of the bottle. Compare it with the product formed when sulfur burns in air.

5. Into the fourth bottle of oxygen thrust a deflagrating spoon containing a *little* (bulk of small match head) red phosphorus that has been previously ignited. Do not inhale the white fumes that are produced, but add a little water to dissolve them when you have finished your observations. *Burn all the phosphorus. Do not throw any of it in the jars or into the sink.*

INSTRUCTOR'S EXPERIMENT:

6. Pour about 50 cc. of water into a bottle of oxygen. Untwist the end of a picture wire a few inches long for about an inch of its length so the wires will be slightly separated. Holding the wire with the tweezers, heat the untwisted end red hot and quickly transfer it to the bottle of oxygen.

OBSERVATIONS: Record your observations for each of the six steps.

QUESTIONS:

1. Why is potassium chlorate used in this experiment?
2. Why was manganese dioxide used?
3. Why should bottles of oxygen stand mouth upward while the gas is being tested?
4. Why should the mouth of the delivery tube be removed from the water as soon as the heating is stopped?

5. Name and define the product that is formed when an element burns in oxygen.

6. How does the white solid formed by burning magnesium in oxygen compare with the residue formed by burning magnesium in air?

7. From a consideration of this experiment, what can you say of the activity of oxygen?

8. Summarize the properties of oxygen under the two headings: *Chemical* and *Physical.*

Complete the following word equations:

9. Potassium chlorate →
10. Carbon + oxygen →
11. Magnesium + oxygen →
12. Sulfur + oxygen →
13. Phosphorus + oxygen →
14. Iron + oxygen →

Experiment 19

STUDY OF THE BUNSEN BURNER

Purpose: To find out how your laboratory burner works.

Apparatus: Bunsen burner; porcelain evaporating dish; tongs; matches; pin; 15-cm. length of glass tubing; glass rod.

Procedure:

1. Unscrew the barrel of the Bunsen burner from its base. Make a vertical cross-section diagram of the burner showing the following parts clearly labeled: *Base, Gas inlet, Ring* or *Collar, Spud, Air inlet,* and *Barrel.*
2. Reassemble the burner and light it. Close the air-inlet holes near the base of the burner. Note the color of the flame.
3. With the tongs hold the bottom of a porcelain evaporating dish in the flame for a minute or two. Note the deposit found on the bottom of the dish.
4. Hold a glass rod in the middle of the flame and note the time required for the glass to soften enough to bend.
5. Open the air-inlet holes by turning the collar. Note the color of the flame.
6. Hold a clean porcelain dish about the middle of the flame. Does a deposit form?
7. Hold a glass rod in the middle of the flame and note the time required to soften the rod enough to bend. How does this time compare with that in step 4?
8. Stick a pin through an unlighted match stick about one-half inch below the head. Using the pin as a support balance the match in the center of the barrel of the burner. Light the burner. Does the flame ignite the match right away?
9. Place one end of a 15-cm. length of glass tubing at just about the center of the barrel of the lighted burner. Hold the tube slanting upward. Bring a lighted match to the upper end of the tube. What is the result?

QUESTIONS:

1. Why is the flame yellow when no air enters the bottom of the burner, and pale blue when air is admitted?
2. In which flame, yellow or blue, is combustion most nearly complete? Give observations to justify your answer.
3. Which of the two flames is the hottest? Give a reason for your answer.
4. Does combustion take place from the tip of the flame to the level of the top of the barrel? Explain.

Experiment 20

DESTRUCTIVE DISTILLATION

PURPOSE: To learn some products formed by distilling soft coal.

APPARATUS: Hard-glass test tube; test tubes; 4-oz. bottle; glass tubing; soft coal; litmus paper.

BACKGROUND: Soft coal, like hard coal, was once living vegetable matter, but it has not been so completely decomposed as hard coal. Hard coal contains from 80 to 90 per cent uncombined carbon. Soft coal contains less free carbon and more carbon which is combined with hydrogen, oxygen, and some other nonmetals. When soft coal is heated in the absence of air in by-product coke ovens, many products such as fuel gas (coal gas), ammonia, benzol, coal tar, and coke are produced.

PROCEDURE:

Arrange the apparatus as shown in Figure 22. Use a hard-glass test tube at *A*, a small bottle at *B*, and a jet tube at *C*. Put several pieces of soft coal in the hard-glass tube and heat them strongly. Light the gas that issues from the jet tube. Examine the liquid that collects in the bottle. Continue to heat *strongly* as long as volatile matter continues to be driven off. Let the tube cool and examine the residue that is left in the tube. Hold a piece of it in the flame. Test some of the liquid in the bottle with both red and blue litmus. (A solution of ammonia turns red litmus blue.) What does the liquid smell like?

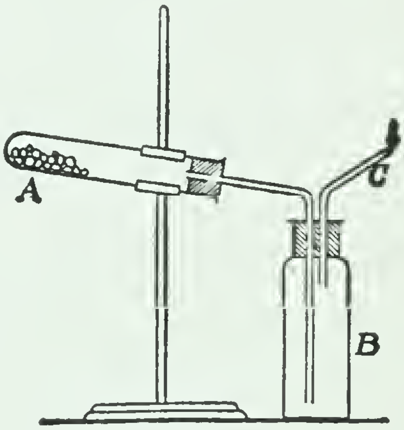


FIG. 22

QUESTIONS:

1. With what color flame did the gas burn?

2. Did the residue left from the distillation of coal burn? What is this residue called? What are two commercial uses for it?

3. Did the litmus test show the presence of ammonia solution in the bottle?

APPENDIX

A

Tables

TABLE 1. — USEFUL NUMBERS

12 in. = 1 ft.
$16\frac{1}{2}$ ft. = 1 rd.
5280 ft. = 1 mi.
9 sq. ft. = 1 sq. yd.
27 cu. ft. = 1 cu. yd.
231 cu. in. = 1 gal.
1 lb. avoir. = 7000 gr.
1 oz. avoir. = 437.5 gr.
1 cu. ft. of water weighs 62.4 lb.
Circumference of a circle = $2\pi r$
Surface of sphere = $4\pi r^2$

3 ft. = 1 yd.
320 rd. = 1 mi.
144 sq. in. = 1 sq. ft.
1728 cu. in. = 1 cu. ft.
2150.4 cu. in. = 1 bu.
60 mi. per hr. = 88 ft. per sec.
1 lb. Troy = 5760 gr.
1 oz. Troy = 480 gr.
$\pi^2 = 9.86965$
Area of circle = πr^2, or $\frac{1}{4}\pi d^2$
Volume of sphere = $\frac{1}{6}\pi d^3$

TABLE 2. — METRIC–ENGLISH EQUIVALENTS

1 in. = 2.5399 cm.
1 mi. = 1609.3 m.
1 mm. = .03937 in.
1 m. = 39.3708 in.
1 m. = 1.0936 yd.
1 sq. in. = 6.451 sq. cm.
1 lb. = 453.593 gm.
1 oz. = 28.3495 gm.

1 ft. = 30.479 cm.
1 mi. = 1.6093 km.
1 cm. = .3937 in.
1 m. = 3.2809 ft.
1 sq. cm. = 0.155 sq. in.
1 cu. in. = 16.3862 cc.
1 kgm. = 2.2046 lb.
1 gm. = 15.432 gr.

TABLE 3. — SPECIFIC WEIGHT OF SOLIDS

Aluminum	2.7	Copper	8.9
Beeswax	0.96	Cork	0.24
Brass	8.2–8.7	Diamond	3.53
Brick	1.4–2.2	Elm	0.58
Bronze	8.7	Glass, crown	2.5
Butter	0.94	Glass, flint	3.0–3.6
Carbon	1.7–3.5	Gold	19.3
Chestnut	0.61	Gold, 18k	14.88
Coal, anthracite	1.26–1.8	Granite	2.65
Coal, bituminous	1.26–1.4	Graphite	2.5

Human body	1.07	Oak	0.85
Ice	0.917	Paraffin	0.824–0.94
Iron, cast	7.1–7.6	Pine	0.46–0.55
Iron, steel	7.79	Platinum	21.4
Iron, wrought	7.8–7.9	Porcelain	2.38
Lead	11.34	Silver	10.5
Lignum vitae	1.33	Silver, sterling	10.38
Limestone	3.18	Sulfur	2.0
Magnesium	1.74	Tin	7.0–7.3
Maple	0.755	Tungsten	18.7
Marble	2.7	Zinc	7.1

TABLE 4. — SPECIFIC WEIGHT OF LIQUIDS

Alcohol, grain	0.794	Mercury	13.56
Alcohol, wood	0.804	Milk	1.029
Carbon bisulfide	1.27	Nitric acid, 68%	1.41
Carbon tetrachloride	1.60	Oil, castor	0.963
Chloroform	1.50	Oil, cottonseed	0.924
Ether	0.72	Oil, linseed	0.94
Gasoline	0.68–0.71	Oil, olive	0.916
Glycerin	1.26	Sulfuric acid	1.84
Hydrochloric acid	1.20	Turpentine	0.87
Kerosene	0.778–0.804	Water, sea	1.026

TABLE 5. — HEAT CONSTANTS

Name	Specific Heat	Melting Point	Boiling Point	Heat of Fusion	Heat of Vaporization
Alcohol	.65	− 130° C.	78° C.		205
Aluminum	.217	657	2200	76.8	
Ammonia		− 75	− 33.5	108	295
Brass	.09	912			
Copper	.093	1065	2310	42	
Glass	.198				
Ice	.5	0		80	
Iron	.113	1550	2450	28	
Lead	.031	327	1525	5.8	
Mercury	.033	− 39	357	2.8	
Platinum	.0323	1760		27.2	
Silver	.056	961	1952	21	
Steam	.48				
Tungsten	.0336	3000			
Water	1.00		100		540
Zinc	.093	419	918	28	

TABLE 6. — TENSILE STRENGTH

Material	Pounds per Square Inch	Material	Pounds per Square Inch
Aluminum......	30,030–40,000	Iron, piano wire	357,000–390,000
Brass...........	50,000–150,000	Lead, drawn...	2600–3300
Bronze wire phosphor.....	110,000–140,000	Platinum, drawn	50,000
Copper, drawn...	60,000–70,000	Silver, drawn...	42,000
Iron, annealed...	50,000–60,000	Steel, ordinary..	80,000–330,000
Iron, hard drawn	80,000–120,000	Steel, maximum	460,000

TABLE 7. — COEFFICIENT OF LINEAR EXPANSION (1° CENTIGRADE)

Quartz.......	.0000005	Iron..........	.000011	Silver.........	.000019
Invar........	.0000009	Steel..........	.000013	Tin...........	.000021
Pyrex........	.000003	Gold..........	.000014	Aluminum....	.000023
Glass........	.000009	Copper......	.000017	Zinc..........	.000029
Platinum.....	.000009	Brass........	.000019	Lead..........	.000029

TABLE 8. — VAPOR PRESSURE OF WATER IN MILLIMETERS OF MERCURY

Degrees C.	Millimeters	Degrees C.	Millimeters	Degrees C.	Millimeters
0	4.5	23	20.9	60	148.9
5	6.5	24	22.2	70	233.3
10	9.1	25	23.5	80	354.7
15	12.7	26	25.0	85	433.1
16	13.5	27	26.5	90	525.4
17	14.4	28	28.1	95	633.7
18	15.3	29	29.8	96	657.7
19	16.3	30	31.5	97	682.1
20	17.3	35	41.6	98	707.3
21	18.5	40	54.8	99	733.2
22	19.6	50	92.0	100	760.0

TABLE 9. — RELATIVE CONDUCTIVITY OF HEAT

Silver	100	German silver	7–8	Magnesia	.016
Copper	92	Mercury	1.6	Paper	.013
Aluminum	48	Concrete	.22	Sawdust	.012
Zinc	27	Glass	.11–.23	Wool	.010
Brass	21–28	Sand, white	.09	Silk	.0095
Platinum	17	Asbestos	.04	Felt	.0087
Iron	12–15	Soil, dry	.033	Air	.005
Steel	6–11.7	Firebrick	.028	Cotton wool	.0043
Lead	8	Linen	.021		

TABLE 10. — DENSITY OF WATER AT VARYING TEMPERATURES

Degrees C.	Grams per Cubic Centimeter	Degrees C.	Grams per Cubic Centimeter	Degrees C.	Grams per Cubic Centimeter
0	.99987	15	.99913	60	.98324
1	.99993	20	.99823	65	.98059
2	.99997	25	.99708	70	.97781
3	.99999	30	.99568	75	.97489
4	1.00000	35	.99406	80	.97183
5	.99999	40	.99225	85	.96865
6	.99998	45	.99025	90	.96534
8	.99987	50	.98807	95	.96192
10	.99973	55	.98573	100	.95838

B

Formulas and Chemical Equations

FORMULAS

1. *Density:* $\mathbf{D} = \frac{\mathbf{W}}{\mathbf{V}}$, or $\mathbf{DV} = \mathbf{W}$

$$\text{Density} = \frac{\text{Weight}}{\text{Volume}}, \text{ or Density} \times \text{Volume} = \text{Weight}$$

2. *Specific Weight of Solids Lighter Than Water:*

$$\textbf{Sp. Wt.} = \frac{w}{w' - w''}$$

$$\text{Sp. Wt.} = \frac{\text{Weight of solid in air}}{\begin{matrix}\text{Combined weight of solid in}\\ \text{air and sinker in water}\end{matrix} - \begin{matrix}\text{Combined weight of}\\ \text{both in water}\end{matrix}}$$

3. *Power:* $\textbf{H.P.} = \frac{fs}{550t}$

$$\text{Horsepower} = \frac{\text{Force in pounds} \times \text{Distance in feet}}{550 \times \text{Time in seconds}}$$

4. *Work Principle:* $\mathbf{E} \times \mathbf{De} = \mathbf{R} \times \mathbf{Dr}$, or $\mathbf{E} \times \mathbf{Ed} = \mathbf{R} \times \mathbf{Rd}$

$$\text{Effort} \times \begin{matrix}\text{Distance effort}\\ \text{moves}\end{matrix} = \text{Resistance} \times \begin{matrix}\text{Distance resistance}\\ \text{moves}\end{matrix}$$

5. *Mechanical Advantage for Any Machine:* $\mathbf{MA} = \frac{\mathbf{R}}{\mathbf{E}}$

$$\text{Mechanical advantage} = \frac{\text{Resistance}}{\text{Effort}}$$

6. *Mechanical Advantage for Any Machine:* $\mathbf{MA} = \frac{\mathbf{De}}{\mathbf{Dr}}$

$$\text{Mechanical advantage} = \frac{\text{Distance effort moves}}{\text{Distance resistance moves}}$$

7. *Lever:* $\mathbf{MA} = \dfrac{\mathbf{EF}}{\mathbf{RF}}$

$$\text{Mechanical advantage} = \frac{\text{Length of effort arm}}{\text{Length of resistance arm}}$$

8. *Efficiency of Lever:* $\dfrac{\mathbf{Dr} \times \mathbf{R}}{\mathbf{De} \times \mathbf{E}}$

$$\begin{array}{c}\text{Efficiency}\\ \text{(of lever)}\end{array} = \frac{\begin{array}{c}\text{Distance which}\\ \text{resistance moves}\end{array} \times \text{Resistance}}{\begin{array}{c}\text{Distance which}\\ \text{effort moves}\end{array} \times \text{Effort}}$$

9. *Use of a Lever of Known Weight to Weigh an Object:*

$$\mathbf{W} \times \mathbf{Dr} = \textbf{Wt. of lever} \times \mathbf{De}$$

$$\begin{array}{c}\text{Unknown}\\ \text{weight}\end{array} \times \begin{array}{c}\text{Distance from W}\\ \text{to the fulcrum}\end{array} = \begin{array}{c}\text{Wt. of}\\ \text{lever}\end{array} \times \begin{array}{c}\text{Distance from fulcrum}\\ \text{to center of gravity}\\ \text{of lever}\end{array}$$

10. *Pulley:* $\mathbf{En} = \mathbf{R}$

$$\text{Effort} \times \begin{array}{c}\text{number of strands}\\ \text{supporting the}\\ \text{movable block}\end{array} = \text{Resistance}$$

11. *Wheel and Axle:* $\mathbf{MA} = \dfrac{\mathbf{C}}{\mathbf{c}} = \dfrac{\mathbf{D}}{\mathbf{d}} = \dfrac{\mathbf{R}}{\mathbf{r}}$

$$\text{Mechanical advantage} = \frac{\begin{array}{c}\text{Circumference}\\ \text{of wheel}\end{array}}{\begin{array}{c}\text{Circumference}\\ \text{of axle}\end{array}} = \frac{\begin{array}{c}\text{Diameter}\\ \text{of wheel}\end{array}}{\begin{array}{c}\text{Diameter}\\ \text{of axle}\end{array}} = \frac{\begin{array}{c}\text{Radius of}\\ \text{wheel}\end{array}}{\begin{array}{c}\text{Radius of}\\ \text{axle}\end{array}}$$

12. *Inclined Plane — Force Applied Parallel to Plane:*

$\mathbf{MA} = \dfrac{\mathbf{1}}{\mathbf{h}}$, or $\mathbf{E : R = h : 1}$

$$\text{Mechanical advantage} = \frac{\text{Length of plane}}{\text{Height of plane}}$$

or

$$\text{Effort} : \text{Resistance} = \begin{array}{c}\text{Height of}\\ \text{incline}\end{array} : \begin{array}{c}\text{Length of}\\ \text{plane}\end{array}$$

13. *Inclined Plane — Force Applied Parallel to Base:* $\mathbf{MA} = \frac{\mathbf{b}}{\mathbf{h}}$

$$\text{Mechanical advantage} = \frac{\text{Base of plane}}{\text{Height of plane}}$$

14. *Screw:* $\mathbf{MA} = \frac{2\pi\mathbf{r}}{\mathbf{d}}$

$$\text{Mechanical advantage} = \frac{2 \times 3.1416 \times \text{Radius of lever upon which the effort acts}}{\text{Distance between the threads of the screw}}$$

15. *Liquid Pressure:* $\mathbf{P} = \mathbf{hd}$

Pressure = Depth of the liquid × The density

16. *Total Force of Liquid Pressure for Horizontal Surfaces:* $\mathbf{F} = \mathbf{Ahd}$

Total force = Area of surface × Depth of liquid × The density

17. *Total Force of Liquid Pressure for Vertical Surfaces:* $\mathbf{F} = \mathbf{A}\frac{\mathbf{h}}{2}\,\mathbf{d}$

$$\text{Total force} = \text{Area of the vertical surface} \times \text{Average depth} \times \text{The density}$$

18. *Hydraulic Press:*

$$\mathbf{MA} = \frac{\mathbf{A}}{\mathbf{a}} \text{ or } \frac{\mathbf{D}^2}{\mathbf{d}^2}\ (\mathbf{E}:\mathbf{R} = \mathbf{a}:\mathbf{A}, \text{ or } \mathbf{E}:\mathbf{R} = \mathbf{d}^2:\mathbf{D}^2)$$

$$\text{Mechanical advantage} = \frac{\text{Area of large piston}}{\text{Area of small piston}} \text{ or } \frac{\text{Diameter of large piston}^2}{\text{Diameter of small piston}^2}$$

or

Effort : Resistance = Area of small piston : Area of large piston

or

$$\text{Effort} : \text{Resistance} = \text{Diameter of small piston}^2 : \text{Diameter of large piston}^2$$

19. *Boyle's Law:* $\mathbf{VP} = \mathbf{V'P'}$

$$\text{Original volume} \times \text{Original pressure} = \text{New volume} \times \text{New pressure}$$

20. *Accelerated Motion:* $V = at$, or $V = gt$

Velocity at end of any given second = Acceleration × time

or

$$\begin{array}{c}\text{Velocity at end of}\\ \text{any given second}\end{array} = \text{Acceleration due to gravity} \times \text{time}$$

21. *Accelerated Motion:* $S = \frac{1}{2}at^2$, or $S = \frac{1}{2}gt^2$

$$\begin{array}{c}\text{Distance for any given}\\ \text{number of seconds}\end{array} = \tfrac{1}{2} \times \text{acceleration} \times \text{time}^2$$

or

$$\begin{array}{c}\text{Distance for any given}\\ \text{number of seconds}\end{array} = \tfrac{1}{2} \times \begin{array}{c}\text{acceleration due}\\ \text{to gravity}\end{array} \times \text{time}^2$$

22. *Accelerated Motion:* $s = \frac{1}{2}a(2t - 1)$, or $s = \frac{1}{2}g(2t - 1)$

$$\begin{array}{c}\text{Distance body moves}\\ \text{in any given second}\end{array} = \tfrac{1}{2} \times \text{acceleration} \times (2 \times \text{time} - 1)$$

or

$$\begin{array}{c}\text{Distance body moves}\\ \text{in any given second}\end{array} = \tfrac{1}{2} \times \begin{array}{c}\text{acceleration due}\\ \text{to gravity}\end{array} \times (2 \times \text{time} - 1)$$

23. *Accelerated Motion:* $V = \sqrt{2aS}$, or $V = \sqrt{2gS}$

$$\begin{array}{c}\text{Velocity at end of}\\ \text{any given second}\end{array} = \sqrt{2 \times \text{acceleration} \times \text{distance}}$$

or

$$\begin{array}{c}\text{Velocity at end of}\\ \text{any given second}\end{array} = \sqrt{2 \times \begin{array}{c}\text{acceleration due}\\ \text{to gravity}\end{array} \times \text{distance}}$$

24. *Pendulum — Law of Lengths:* $t : t' = \sqrt{l} : \sqrt{l'}$

$$\begin{array}{c}\text{Time of}\\ \text{vibration}\\ \text{of first}\\ \text{pendulum}\end{array} : \begin{array}{c}\text{Time of}\\ \text{vibration}'\\ \text{of second}\\ \text{pendulum}\end{array} = \sqrt{\begin{array}{c}\text{length of first}\\ \text{pendulum}\end{array}} : \sqrt{\begin{array}{c}\text{length of second}\\ \text{pendulum}'\end{array}}$$

25. *Pendulum — Time of vibration:*

$$t = \pi\sqrt{\frac{l}{g}},\ \text{or } t^2 = \frac{\pi^2 l}{g}$$

$$\text{Time} = 3.1416 \times \sqrt{\frac{\text{length of pendulum}}{\text{acceleration due to gravity}}}$$

or

$$\text{Time}^2 = 3.1416 \times 3.1416 \times \frac{\text{length of pendulum}}{\text{acceleration due to gravity}}$$

26. *Acceleration Is Directly Proportional to Force:*

$$\mathbf{f : f' = a : a', \text{ or } f : W = a : g}$$

$$\begin{matrix}\text{Original}\\\text{force}\end{matrix} : \begin{matrix}\text{New}\\\text{force}\end{matrix} = \begin{matrix}\text{Original}\\\text{acceleration}\end{matrix} : \begin{matrix}\text{New}\\\text{acceleration}\end{matrix}$$

or

$$\text{Force} : \begin{matrix}\text{Weight of}\\\text{moving object}\end{matrix} = \text{Acceleration} : \begin{matrix}\text{Acceleration due}\\\text{to gravity or weight}\end{matrix}$$

27. *Centrifugal Force:* $\mathbf{C.F. = \frac{mv^2}{gr}}$

$$\begin{matrix}\text{Centrifugal force}\\\text{in grams}\end{matrix} = \frac{\begin{matrix}\text{Mass in}\\\text{grams}\end{matrix} \times \begin{matrix}\text{Velocity in}\\\text{centimeters}^2\end{matrix}}{\begin{matrix}\text{Acceleration due}\\\text{to gravity}\end{matrix} \times \begin{matrix}\text{Radius in}\\\text{cm.}\end{matrix}}$$

$$\begin{matrix}\text{Centrifugal force}\\\text{in pounds}\end{matrix} = \frac{\begin{matrix}\text{Mass in}\\\text{pounds}\end{matrix} \times \begin{matrix}\text{Velocity in}\\\text{feet}^2\end{matrix}}{\begin{matrix}\text{Acceleration due}\\\text{to gravity}\end{matrix} \times \begin{matrix}\text{Radius in}\\\text{feet}\end{matrix}}$$

28. *Centigrade to Absolute Temperature:* $\mathbf{T = t + 273^\circ}$

$$\text{Absolute temperature} = \text{Centigrade temperature} + 273^\circ$$

29. *Law of Charles:* $\mathbf{V : V' = T : T'}$

$$\begin{matrix}\text{Original}\\\text{volume}\end{matrix} : \begin{matrix}\text{New}\\\text{volume}\end{matrix} = \begin{matrix}\text{Original absolute}\\\text{temperature}\end{matrix} : \begin{matrix}\text{New absolute}\\\text{temperature}\end{matrix}$$

30. *Laws of Boyle and Charles:* $\mathbf{\frac{PV}{T} = \frac{P'V'}{T'}}$

$$\frac{\begin{matrix}\text{Original}\\\text{pressure}\end{matrix} \times \begin{matrix}\text{Original}\\\text{volume}\end{matrix}}{\text{Original absolute temperature}} = \frac{\begin{matrix}\text{New}\\\text{pressure}\end{matrix} \times \begin{matrix}\text{New}\\\text{volume}\end{matrix}}{\text{New absolute temperature}}$$

31. *Power Formula of Society of Automotive Engineers* (S.A.E.):

$$\text{H.P.} = \frac{D^2N}{2.5}$$

$$\text{Horsepower} = \frac{\begin{array}{c}\text{Cylinder diameter}\\ \text{in inches}^2\end{array} \times \begin{array}{c}\text{Number of}\\ \text{cylinders}\end{array}}{2.5}$$

32. *Indicated Horsepower:* $\text{I.H.P.} = \frac{PLANK}{33{,}000}$

$$\begin{array}{c}\text{Indicated}\\ \text{horsepower}\end{array} = \frac{\begin{array}{c}\text{Average pressure}\\ \text{during power stroke}\\ \text{in lbs. per sq. in.}\end{array} \times \begin{array}{c}\text{Length of}\\ \text{piston stroke}\\ \text{in feet}\end{array} \times \begin{array}{c}\text{Area of}\\ \text{cylinder}\\ \text{in sq. in.}\end{array} \times \begin{array}{c}\text{Number of}\\ \text{power strokes}\\ \text{per minute}\end{array} \times \begin{array}{c}\text{Number of}\\ \text{cylinders}\end{array}}{33{,}000}$$

CHEMICAL EQUATIONS

1. *Burning Carbon:* $C + O_2 \rightarrow CO_2$

One atom of carbon plus one molecule of oxygen combine to form one molecule of carbon dioxide.

C is the symbol for carbon; CO_2, the formula for one molecule of carbon dioxide.

2. *The Preparation of Water Gas By Passing Steam Over White-Hot Coke (Carbon):* $C + H_2O \rightarrow CO\uparrow + H_2\uparrow$

One atom of white-hot carbon (coke) plus one molecule of water, in the form of steam, produces one molecule of carbon monoxide gas plus one molecule of hydrogen gas. A mixture of CO and H_2 is known as water gas.

C is the symbol for carbon; H_2O, the formula for water; CO, the formula for carbon monoxide; H, the symbol for hydrogen.

3. *The Preparation of Acetylene Gas:*

$$CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2\uparrow$$

Calcium carbide plus water forms calcium hydroxide plus acetylene gas.

Ca is the symbol for calcium; CaC_2, the formula for one molecule of calcium carbide; $Ca(OH)_2$, the formula for one molecule of calcium hydroxide (commonly known as lime); C_2H_2, the formula for one molecule of acetylene gas.

4. *The Endothermic Reaction for the Formation of Acetylene Gas:*

$$2C + H_2 + 58{,}100 \text{ calories} \rightarrow C_2H_2 \uparrow$$

Two atoms of carbon plus one molecule of hydrogen plus 58,100 calories form acetylene gas.

C is the symbol for carbon; H_2, the formula for one molecule of hydrogen; C_2H_2, for acetylene gas.

5. *The Burning of Acetylene Gas — A Highly Exothermic Reaction:*

$$2C_2H_2 + 5O_2 \rightarrow 4CO_2 \uparrow + 2H_2O + 641{,}000 \text{ calories}$$

Two moles (gram molecules) of acetylene gas plus five molecules of oxygen gas form four molecules of carbon dioxide plus two molecules of water plus 641,000 calories.

C_2H_2 is the formula for acetylene gas; O_2, the symbol for one molecule of oxygen gas; CO_2, the formula for one molecule of carbon dioxide; H_2O, the formula for water.

C

Mathematical Pointers

I. WHAT ARE THE EQUATIONS — FORMULAS — USED IN PHYSICS?

The equations used in physics are all formulas; that is, they are shorthand methods of showing equalities and relationships. They simplify your work, save time, and make numerical substitution much easier and simpler.

Algebra teaches that each side of an equation may be multiplied or divided by the same quantity without altering the relationship between the two parts of the equation. In the same way, the same quantity may be added to or subtracted from each side of an equation without changing its value.

To illustrate, a certain army camp has an area of 5 sq. miles. Let the letter a, or any other symbol that you decide upon, stand for the area, and you can write a formula to state this fact:

$$a = 5$$

A second camp is only one-fifth as large as the first. Obviously, it has an area of 1 sq. mile. You can set up an equation for this, too:

$$\frac{a}{5} = \frac{5}{5}$$

A third camp is five times as large as the first. Its area is, of course, 25 sq. miles. Another equation makes this clear:

$$5a = 5 \times 5 \qquad 5a = 25$$

Suppose, on the other hand, that 2 sq. miles were taken from the area of the first camp. Obviously, it would then have an area of 3 sq. miles. Expressed in an equation this would read:

$$a - 2 = 5 - 2 \qquad a - 2 = 3$$

Finally, suppose that the first camp were increased in size by 2 sq. miles. Its area would then be 7 sq. miles, and the equation would read:

$$a + 2 = 5 + 2 \qquad a + 2 = 7$$

EQUATIONS—FORMULAS OF THE CIRCLE

The *circumference* of a circle is 3.14159 . . . times as long as the *diameter.* (See Fig. C–1.) This number contains a decimal which never ends; it is commonly referred to as π (pronounced "pie"), and for purposes of convenience is used as $\frac{22}{7}$ or 3.1416 in numerical calculations.

How do you find the circumference of a circle? The fact that the circumference is equal to the diameter multiplied by π can be easily expressed in a formula. Let D equal the *diameter,* C the *circumference,* and π equal 3.1416:

$$C = \pi D$$

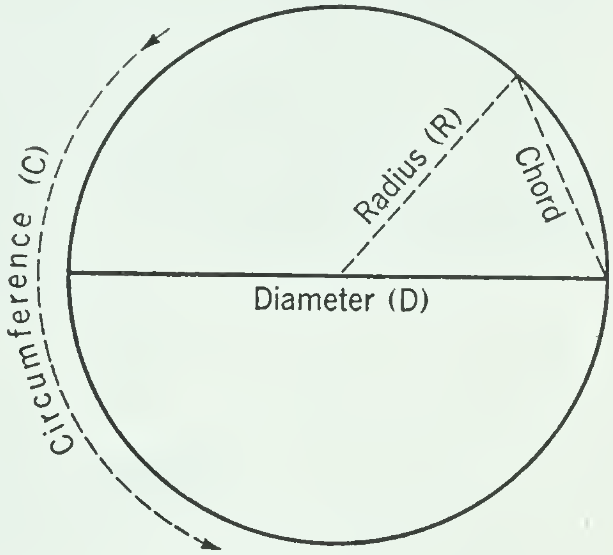


FIG. C–1.

We can make use of the *radius, R,* which is equivalent to ½ the diameter in this same formula:

$$C = 2\pi R$$

How do you find the area of a circle? To find the area of a circle, you multiply the radius of the circle by itself, and then by π. This is equivalent to saying that $A = \pi \times R \times R$, or:

$$A = \pi R^2$$

PROBLEM. An observation plane flies in a circle ten miles out from a beach-head. What distance does the plane travel in making a complete circle?

Solution. The distance of ten miles is the radius of the circle which the plane flies about the beach-head. Given the radius of the circle, it is simple to determine its circumference.

$$C = 2\pi R$$

$$C = 2 \times 3.1416 \times 10$$

$$C = 62.832 \text{ miles}$$

How do you find the radius of a circle? To find the radius of a circle, the circumference of which is known, you use the formula $C = 2\pi R$, and substitute.

Problem. Making a fifty-mile circle directly around the Jap installations on Wake Island, a scouting plane spots a convoy directly beneath it. At what distance from the island is the convoy?

Solution. Fifty miles is the circumference of the circle flown by the plane. The convoy is distant from the island the length of the radius of the circle. We know that $C = 2\pi R$. We therefore substitute in this formula and solve for R.

$$C = 2\pi R$$

$$50 = 2 \times 3.1416 \times R$$

$$50 = 6.2832R$$

$$6.2832R = 50$$

$$R = 7.95 \text{ miles}$$

EQUATIONS — FORMULAS OF THE RIGHT TRIANGLE

A *triangle* is a three-sided figure with three angles; the sum of these three angles is always 180°.

A *right triangle* is one which contains one angle of 90°. The long arm of a right triangle, that is, the arm opposite the 90° angle, is called the *hypotenuse.* A knowledge of the right triangle is basic to all physical science and you rarely bother to write out the word; you simply use a sign for it: ◺

If you know the length of any two arms of a ◺ you can, very simply, calculate the length of the third arm.

How do you find the length of the hypotenuse of a ◺? Suppose you let the letter a stand for the length of the hypotenuse, the letters b and c the length of the other two arms. You can set up a formula which is easy to remember.

$$a^2 = b^2 + c^2$$

This formula is pictured in Figures C–2, C–3, and C–4. It's clear that:

(1) a^2 means the square of the side which is a units long.
(2) b^2 means the square of the side which is b units long.
(3) c^2 means the square of the side which is c units long.

In all cases, $b^2 + c^2 = a^2$. Therefore, you can say that **in any ◺, the square of the hypotenuse is equal to the sum of the squares of the other two sides.**

Your formula to find the hypotenuse of any ◺ is $a^2 = b^2 + c^2$.

If arm c in Figure C–3 is really 3 miles long and arm b is 4, what is the length of the hypotenuse, or longest arm, a? First, state the formula, then solve with the known quantities:

$$a^2 = b^2 + c^2$$

$$a^2 = (4)^2 + (3)^2$$

$$a^2 = (4 \times 4) + (3 \times 3)$$

$$a^2 = 16 + 9$$

$$a^2 = 25$$

$a = 5$, for $(5)^2$, that is 5×5, equals 25. In other words a (5) is *the square root* of a^2 (25).

You can, of course, state the formula for a rather than for a^2, if you wish.

$a =$ the square root of $b^2 + c^2$, or, as it is most often written for convenience:

$$a = \sqrt{b^2 + c^2}$$

How do you find the length of the two shorter arms of a ◺? The beauty of a formula is that you can use it to set up a value for any element in it. You know that $a^2 = b^2 + c^2$.

Suppose you know the value of a, the hypotenuse, and the

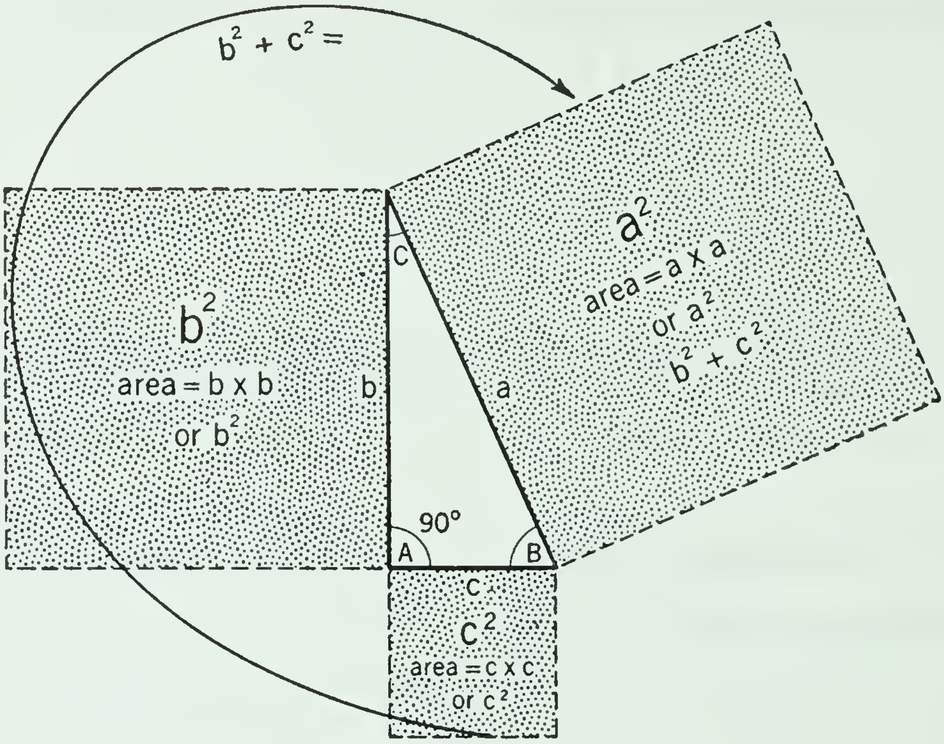

$b^2 + c^2 =$
a^2
area = a x a
or a^2
$b^2 + c^2$
b^2
area = b x b
or b^2
b
C
a
90°
A
B
c
c^2
area = c x c
or c^2

FIG. C–2.

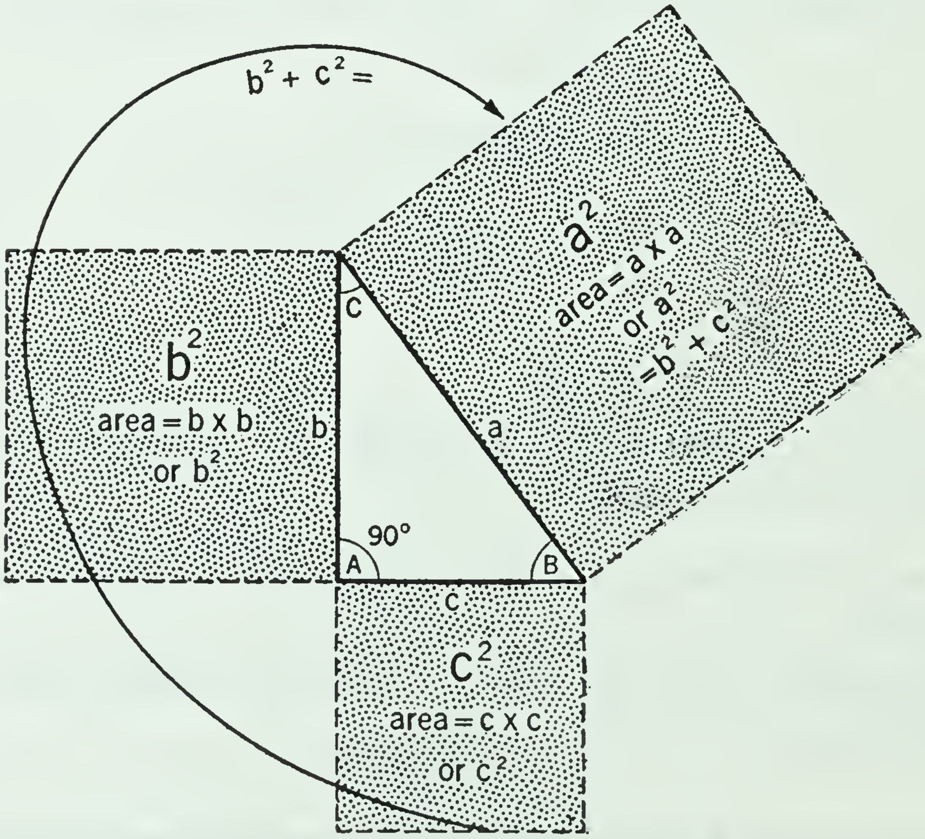

$b^2 + c^2 =$
a^2
area = a x a
or a^2
$= b^2 + c^2$
b^2
area = b x b
or b^2
b
C
a
90°
A
B
c
c^2
area = c x c
or c^2

FIG. C–3.

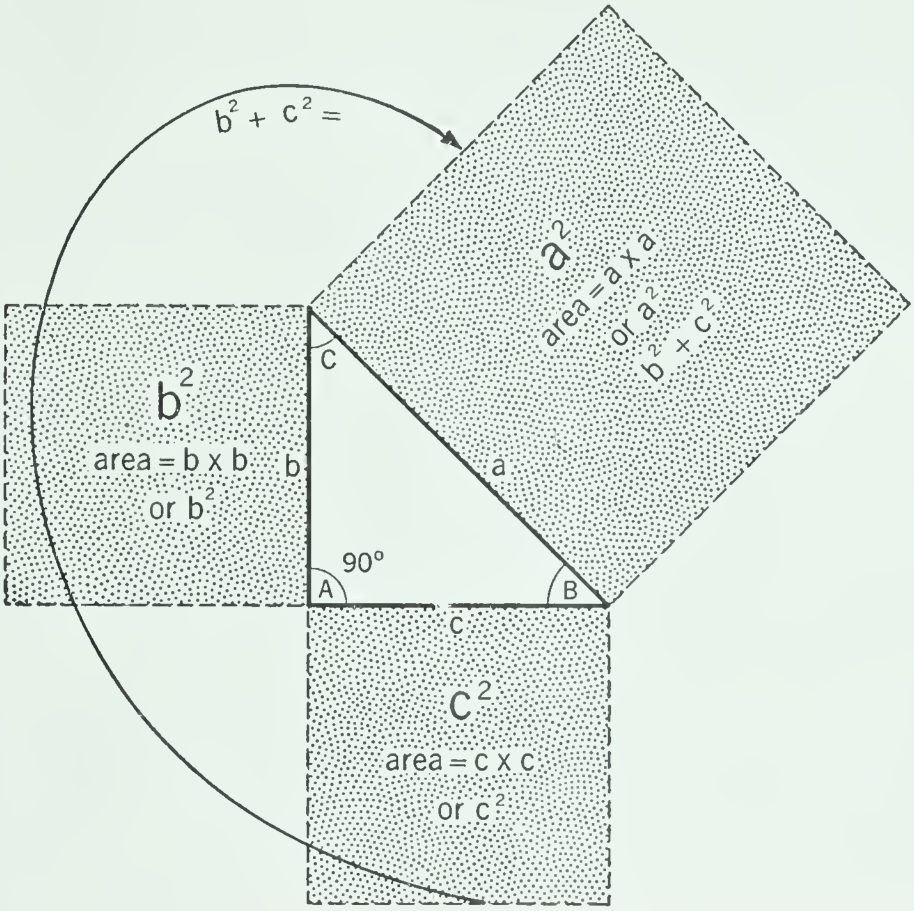


FIG. C–4.

value of one of the shorter arms b or c. What formula would you use to find the value of the arm of unknown length?

Starting with $a^2 = b^2 + c^2$, you can see that $a^2 - b^2 = c^2$. Therefore,

$$c^2 = a^2 - b^2 \quad \text{and} \quad c = \sqrt{a^2 - b^2}$$

You can see that $a^2 - c^2 = b^2$. Therefore,

$$b^2 = a^2 - c^2 \quad \text{and} \quad b = \sqrt{a^2 - c^2}$$

PROBLEM. The hypotenuse, a, is 5 miles long, and one of the short arms, b, is 4 miles long. What is the length of the arm c?

Solution.

$$c = \sqrt{a^2 - b^2}$$

$$c = \sqrt{(5)^2 - (4)^2}$$

$$c = \sqrt{(5 \times 5) - (4 \times 4)}$$

$$c = \sqrt{25 - 16}$$

$$c = \sqrt{9}, = 3$$

PROBLEM. The hypotenuse, a, is 5 miles long, and the short arm, c, is 3 miles long. What is the length of b?

Solution.

$$b = \sqrt{a^2 - c^2}$$

$$b = \sqrt{(5)^2 - (3)^2}$$

$$b = \sqrt{(5 \times 5) - (3 \times 3)}$$

$$b = \sqrt{25 - 9}$$

$$b = \sqrt{16}, = 4$$

What are three important types of ◺s? Figures C–2, C–3, and C–4 show three different types of ◺s.

In Figure C–2, angle B is 60°, and angle C is 30° (for the sum total of degrees of the angles of a triangle is 180°). The arm c is $\frac{1}{2}$ the length of arm b.

In Figure C–3 the proportionate length of the three arms is 5, 4, and 3. You have already seen that you deal only with perfect squares in calculating the length of any arm of this triangle. This continues to be true with ◺s whose sides are whole-number multiples of 3, 4, and 5. For example, you continue to work with perfect squares in a ◺ whose hypotenuse is 25 units long, and whose legs are 20 and 15 units long respectively.

In Figure C–4, angle B is 45° and angle C is 45°. The two arms b and c are of equal length.

How do you find square root? When, for example, the sum of $b^2 + c^2$ in the equation $a^2 = b^2 + c^2$ is not a perfect square, it becomes necessary to take the square root of their sum. Turn to page 519 for illustrations which show you how to take the square root of any number.

EQUATIONS — FORMULAS OF PHYSICAL RELATIONSHIPS

$D = \frac{W}{V}$. The first physics equation or formula of importance is that which shows the relation between density, weight, and volume, or $D = \frac{W}{V}$ where D stands for *density*, W for *weight*, and V for *volume*.

If you know W and V and wish to find D, it is a simple matter to substitute the numerical values for W and V and to perform the indicated division. But suppose that you know D and W and wish to find the value of V. We say that it is necessary to solve the equation for V. It is generally easier to do this before numerical values are substituted for the known quantities. So if we multiply each side of our equation $D = \frac{W}{V}$ by $\left(\frac{V}{D}\right)$, $\cancel{D}\frac{V}{\cancel{D}} = \frac{W}{\cancel{V}}\left(\frac{\cancel{V}}{D}\right)$. After cancelling the D's and the V's we have

$$V = \frac{W}{D}$$

Similarly W may be found by multiplying the equation by V. $D \times V = \frac{W}{\cancel{V}} \times \cancel{V}$ or:

$$W = DV$$

$A = \pi\left(\frac{D}{2}\right)^2$. If the area of a circle is A and we let D stand for its diameter, we may write the equation for its area:

$$A = \pi\left(\frac{D}{2}\right)^2 = \pi\frac{D^2}{4}$$

Likewise we may write the formula for another circle, one which has an area, a, and a diameter, d:

$$a = \pi\left(\frac{d}{2}\right)^2 = \pi\frac{d^2}{4}$$

Now we may divide the first equation by the second since we are dividing each side of the first equation by quantities which are equal to each other:

$$\frac{A}{a} = \frac{\dfrac{\cancel{\pi}D^2}{\cancel{4}}}{\dfrac{\cancel{\pi}d^2}{\cancel{4}}}$$

π cancels out, as do the 4's, so that we have

$$\frac{A}{a} = \frac{D^2}{d^2}$$

We read such an equation as: "large A over small a equals large D squared over small d squared." We may also read it as: "the area of circle large A is to the area of circle small a as the square of the diameter of circle large A is to the square of the diameter of circle small a." You will sometimes see this relationship written in proportionate form: $A : a = D^2 : d^2$.

$\frac{R}{E} = \frac{D^2}{d^2}\cdot$ The mechanical advantage MA of a hydraulic press whose large piston is of area A and whose small piston has an area a, is given as $\frac{A}{a}\cdot$ Since $\frac{A}{a} = \frac{D^2}{d^2}$, the MA of the press must equal $\frac{D^2}{d^2}\cdot$ In dealing with equations and formulas we make a great deal of use of a fundamental principle: things equal to the same thing are equal to each other. But the MA of the hydraulic press is also equal to $\frac{R}{E}$ where R is the resistance on the large piston A, and E is the effort applied to the small piston a. It follows then, that:

$$\frac{R}{E} = \frac{D^2}{d^2}$$

In an equation of this sort any one of the quantities may be found, if the other three are known, by solving the equation for the unknown quantity (see page 515) and substituting the proper numerical values for the known quantities and performing the indicated computation. In this particular equation D and d will always be known since they can be easily measured.

The equation $\frac{R}{E} = \frac{D^2}{d^2}$ may also be written $Rd^2 = ED^2$ and it is sometimes easier to work from it in this form. You can see from this form that $R = E\frac{D^2}{d^2}$ or that $E = \frac{d^2}{D^2}R$.

$\frac{V}{V'} = \frac{P'}{P}\cdot$ In problems dealing with Boyle's Law we meet the same sort of relationship, $VP = V'P'$, which is frequently written $\frac{V}{V'} = \frac{P'}{P}\cdot$ V' and P' are read "V prime" and "P prime." They stand for *new volume* and new pressure, respectively.

There is this difference: the areas of two circles vary *directly* as the squares of their diameters, while the old and new volumes of a gas vary *inversely* as the pressures they sustain.

$El = Rh$. We encounter this sort of proportionate equality again in connection with the inclined plane, where the effort E, if applied parallel to the plane, is to the resistance R as the height of the plane h is to the length of the plane l or $\frac{E}{R} = \frac{h}{l}$ which may be written $E : l = R : h$ and solved for the unknown quantity, if the other three are known.

$\frac{t}{t'} = \frac{\sqrt{l}}{\sqrt{l'}}\cdot$ In connection with the pendulum we have a similar relationship $\frac{t}{t'} = \frac{\sqrt{l}}{\sqrt{l'}}\cdot$ If we square each side we have $\frac{t^2}{(t')^2} = \frac{l}{l'}$, or $t^2l' = (t')^2l$ and we can solve the equation for the quantity whose value we wish to determine and proceed as usual. t' and l' are read "t prime" and "l prime." They stand for *new time of vibration* and *new length*, respectively.

$\frac{f}{W} = \frac{a}{g}\cdot$ The very useful equation $\frac{f}{W} = \frac{a}{g}$ which is derived in the discussion of Newton's second law of motion is another example of this sort of proportionate equality.

II. WHAT IS MEANT BY ALGEBRAIC SUM?

The term *algebraic sum* is used frequently in our explanation and discussions. When we say that the algebraic sum of parallel forces acting upon a rigid bar is zero, we mean that the forces acting vertically upward equal the forces acting vertically downward. The same explanation applies to moments. If the counterclockwise moments equal the clockwise moments, their algebraic sum is zero. If we agree to say that forces acting vertically upward and moments acting counterclockwise are positive or plus values, it is clear that we must consider forces acting vertically downward and moments acting clockwise as negative or minus values. For equilibrium these forces and moments must balance, that is their algebraic sum must be zero.

Consider the problem illustrated in Figure C–5.

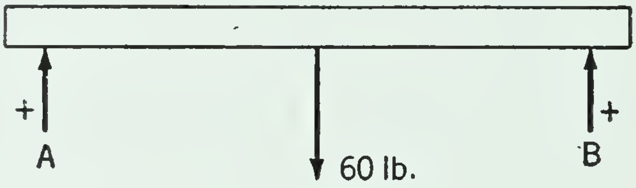


Fig. C–5.

The 60-lb. bar which is of uniform weight throughout its length is supported at points *A* and *B*, equidistant from the ends of the bar. Since the downward force of 60 lb. acts at the center of gravity which is the middle of the bar, the loads on *A* and *B* are equal or each support exerts an upward push of 30 lb. There is no motion because the forces pushing upward are equal and opposite to the downward force of 60 lb. If we say the forces upward are *positive*, then we must call the 60-lb. force *negative*. We may show that the algebraic sum is zero in this way: $30 + 30 + (-60) = 30 + 30 - 60 = 0$. In scientific work we use the minus sign to indicate direction, not subtraction, but when we add positive and negative quantities, we do in effect subtract one from the other.

Consider a bar pivoted so as to turn about an axis part way along its length. (See Fig. C–6.) Two forces act clockwise and

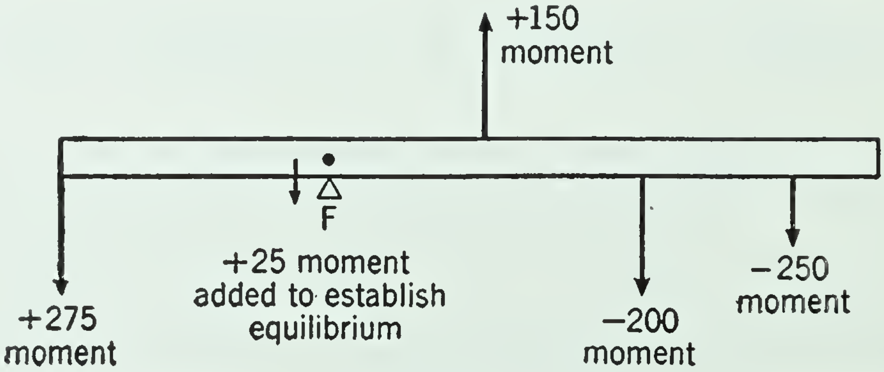


Fig. C–6.

two act counterclockwise. Their moments are -200, -250, 275, and 150 respectively. The sum of the counterclockwise moments is 425. Clearly $-450 + 425 = -25$ and not 0. This tells us that the bar will rotate in a clockwise direction since the algebraic sum of the moments is not 0 and the clockwise moments exceed the counterclockwise moments.

The bar may be balanced and equilibrium established if a force of 25 lb. is added one foot to the left of the fulcrum so as to produce an additional counterclockwise moment of 25. Then $-450 + 425 + 25 = 0$ and we say the algebraic sum of the moments is 0.

III. HOW CAN YOU FIND THE SQUARE ROOT?

Example 1. To find the square root of a number with an *even* number of figures to the left of the decimal point — such as 1398.76.

$$\begin{array}{r|l} & 3\ \ \ 7\ \ .4 \\ \hline 3 & 13/98/.76/ \\ 3 & \ 9 \\ \hline 67 & 498 \\ 7 & 469 \\ \hline 744 & 2976 \\ & 2976 \\ \hline \end{array}$$

$$\therefore \quad \sqrt{1398.76} = 37.4$$

Steps in Working

(1) Starting from the decimal point, mark off the figures two at a time, so that you have 13, 98, 76.

(2) Get the square root of 13, or of the perfect square below it, 3.

(3) Put this 3 in the answer and also in the divisor and proceed as in ordinary division; $3 \times 3 = 9$.

(4) Now make a new dividend and a new divisor. Subtract 9 from $13 = 4$ and bring down the next pair of figures, 98, thus making the new dividend 498.

Add the last figure in the answer, 3, to the last divisor, $3, = 6$.

(5) Now your new divisor will be sixty something, the "something" being the same number both in the answer and in the divisor. Try 8;

8 × 68 = 544 is too great; 7 will do. 7 is the next figure in the divisor and the answer.

(6) 67 × 7 = 469 from 498 leaves 29, and so 2976 becomes the new dividend.

(7) Add 7, the last figure in the answer, to the last figure in the divisor, 67 + 7 = 74.

(8) Get your last figure in the answer, 4, as in step (5).

Example 2. To find the square root of a number with an *odd* number of figures to the left of the decimal point — such as 660.49. Here we start by getting the square root of 6 and then proceed as in Example 1.

$$\begin{array}{r|l}
 & 2\ \ 5\ .7 \\ \hline
2 & 6'60'.49' \\
2 & 4 \\ \hline
45 & 260 \\
5 & 225 \\ \hline
507 & 3549 \\
 & 3549 \\ \hline
\end{array}$$

$$\therefore \quad \sqrt{660.49} = 25.7$$

Note carefully the position of the decimal point in the square root.

Example 3. To find the square root of a number whose square root does not work out exactly — such as 164.8. Add as many zeros as are necessary.

$$\begin{array}{r|l}
 & 1\ \ 2\ .8\ \ \ 3 \\ \hline
1 & 1'64'.80'00' \\
1 & 1 \\ \hline
22 & \ \ 64 \\
2 & \ \ 44 \\ \hline
248 & 2080 \\
8 & 1984 \\ \hline
2563 & 9600 \\
 & 7689 \\ \hline
\end{array}$$

12.83 is the approximate square root of 164.8.

IV. HOW IS THE PROTRACTOR USED?

A protractor is a device for measuring and laying off angles. Many protractors are so constructed as to have also a 5- or 6-inch ruler or scale and a centimeter scale. The protractor consists of an arc of 180° (half a circle) which is usually divided into two scales. One starts from the right and ends at the left, numbering the degrees from 0° to 180°. The other starts from the left and numbers the degrees from 0° to 180° to the right. Sometimes it is convenient to use one scale, sometimes the other.

At the midpoint of the diameter of the arc is an arrow which must always be centered on the point from which the angle is being measured. The diameter edge or line must fall upon or coincide with the reference line from which angle measurements are being made.

When angle measurements are to be made above a horizontal line the protractor is placed upon the line so that the diameter

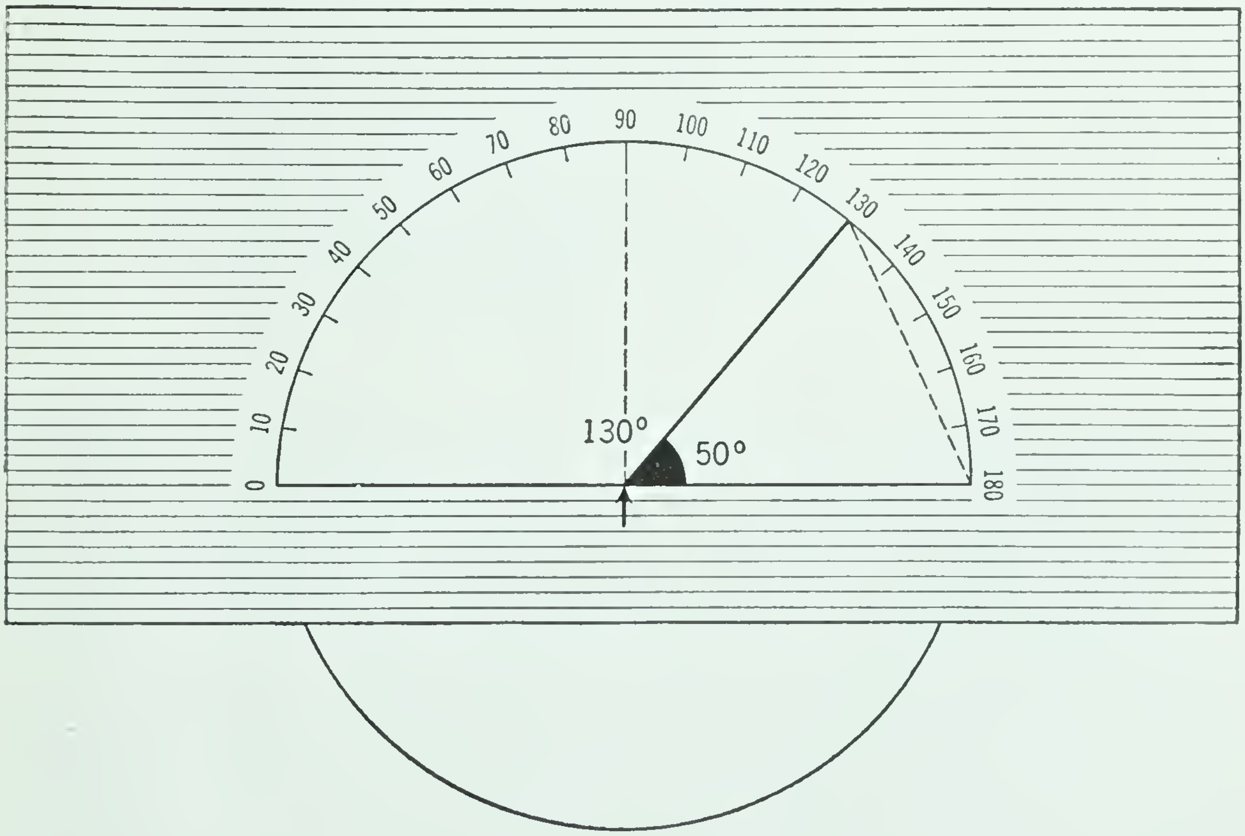


Fig. C–7.

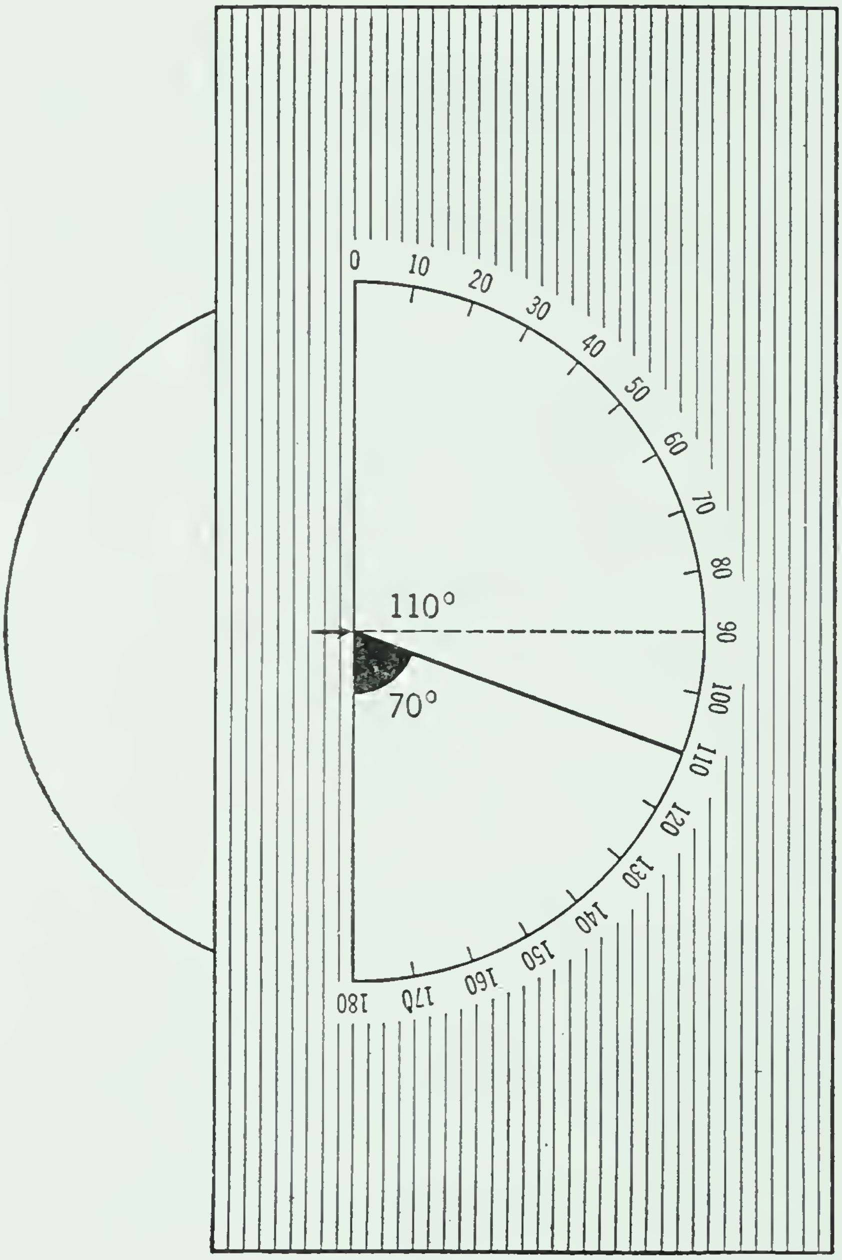


FIG. C–8.

coincides with it and the arrow is over the point from which the angle is being measured. The scale is above the line.

When angles are being measured below a horizontal line the protractor is placed on the line as before except that it is tipped upside down so that the scale is below the line.

If your reference line is vertical, the protractor scale is placed either to the right or to the left of the line, depending on which side of the line the angle is to be measured. If the line is inclined the protractor is placed on the line so that the scale falls upon

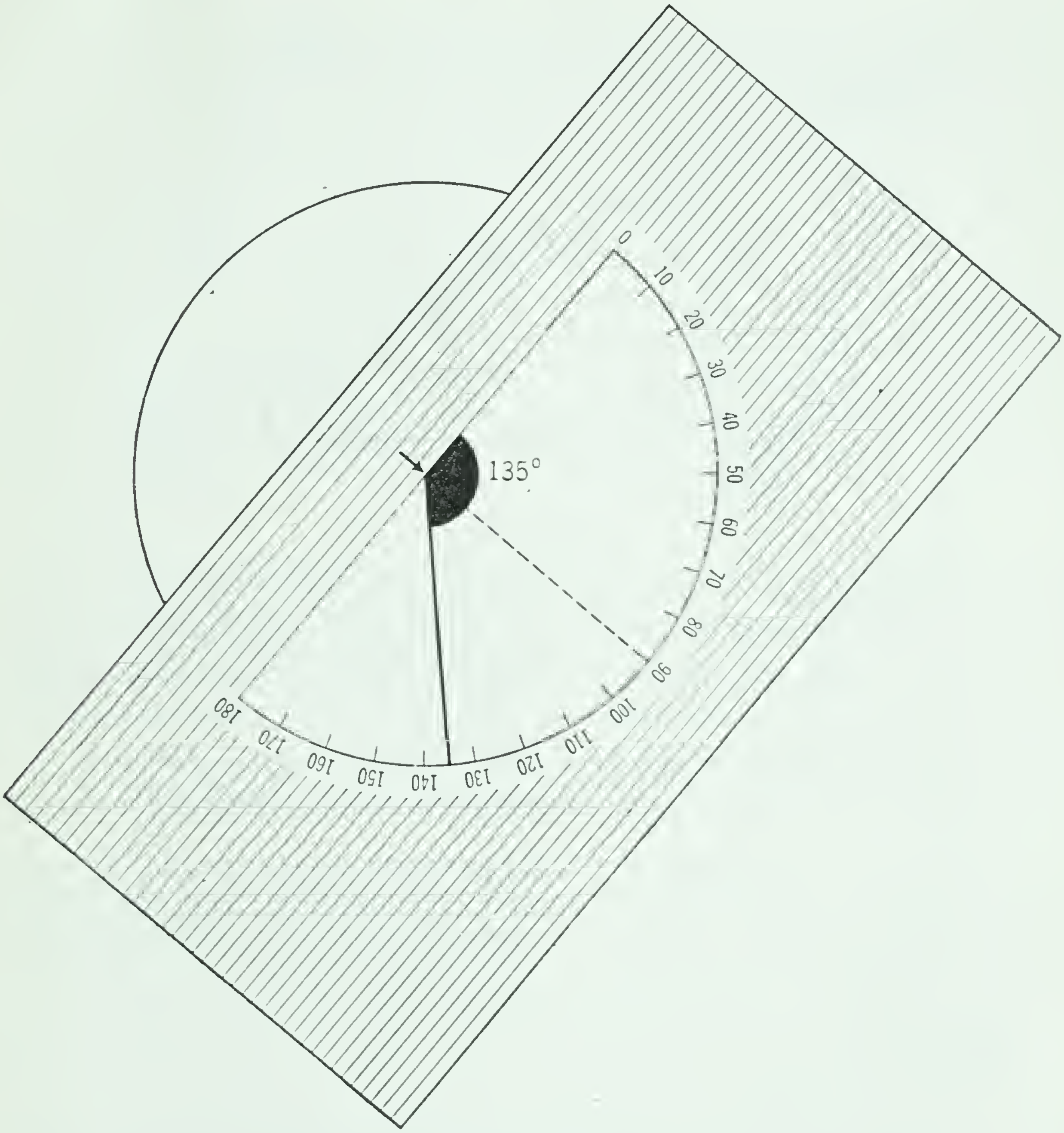


Fig. C–9.

the side on which the angle is being laid off. Note the procedure followed in each of the drawings shown in Figures C–7, C–8, and C–9.

V. HOW ARE PROBLEMS SOLVED GRAPHICALLY?

In this book most of the problems on the composition and resolution of forces and velocities are to be solved graphically. That is, the known forces are laid out to scale (for example, you let 1 cm. = 5 lb., as in Fig. C–10) along lines drawn in the direction in which they act from the point at which they are applied.

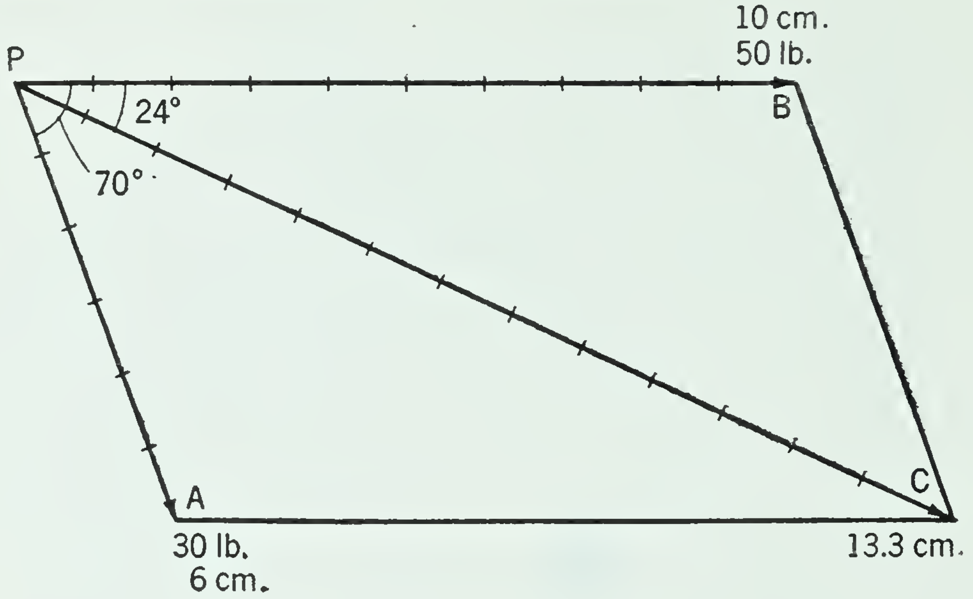


FIG. C-10.

The parallelogram is completed and the unknown force determined by measuring the length of the side or diagonal which represents it. The one exception is when forces act at right angles and the unknown force may be calculated from the relationship existing between the squares of the sides of a right triangle.

A few problems and their solution will make this clear.

PROBLEM 1. Given a force of 50 lb. acting in an easterly direction upon a point *P*. A second force of 30 lb. acts upon the point at an angle of 70° in a southeasterly direction. What is the direction and magnitude of the resultant?

(Use a sharp pencil in your work.)

Solution.

(1) Let 1 cm. equal 5 lb. of force.

(2) Measure 10 cm. to the right along a horizontal line from *P* giving the line *PB*, the graphic representation of the force of 50 lb. acting in an easterly direction.

(3) Place your protractor upside down upon the line *PB* and lay off an angle of 70° measured from the left.

(4) Lay off *PA* on this line 6 cm. in length for a graphic representation of the force of 30 lb. acting upon *C* in a southeasterly direction.

(5) Place your protractor upon the line *PA* so that the point of the arrow falls on *A* and the diameter line falls on *PA*. Lay off an angle of 70° measuring from the right, or 110° measuring from the left, and draw the line.

(6) Similarly place the protractor upon *B* and lay off an angle of 70° measuring from the left.

(7) The point of intersection of these two lines is C, and the line PC is the graphic representation of the resultant of these two forces of 50 and 30 lb. Note that AC and BC are parallel to PB and PA respectively.

(8) Measure accurately the line PC. It measures 13.3 cm. $13.3 \times 5 = 66.5$ lb., the value of the resultant force.

(9) Measuring the angle BPC, which is 24°, gives the direction in which the resultant acts from a due easterly direction.

PROBLEM 2. A force of 70 lb. acts in a northeasterly direction upon a point P while an unknown force acts upon the point to produce a resultant force of 50 lb. acting at an angle of 58° measured in a clockwise direction from the line of application of the first force. What is the value of the unknown component and the angle which it makes with the resultant force?

Solution.

(1) Let 1 cm. equal 10 lb. of force.

(2) From a point P, draw a line in a northeasterly direction. (See Fig. C-11.) Measure off on this line 7 cm. to represent the force of 70 lb. by the line PA.

(3) From P and the line PA lay off an angle of 58° clockwise and draw the line.

(4) Measure off the line PB, 5 cm. long, to represent the resultant force.

(5) Connect A and B and measure the line AB. It measures 6 cm., making the unknown force 60 lb. in magnitude.

(6) The angle PAB is found to be 45°.

(7) With arrow at P and the diameter line on PA lay off the angle PAB, 45° in this problem, measured from the right, 135° if measured from the left.

(8) The angle BPC is found to be 77° by measurement.

(9) The parallelogram can be completed by measuring off 6 cm. on PC and drawing BC or by laying off an angle of 58° measured from the right at B on the line PB and drawing the line until it intersects C on PC.

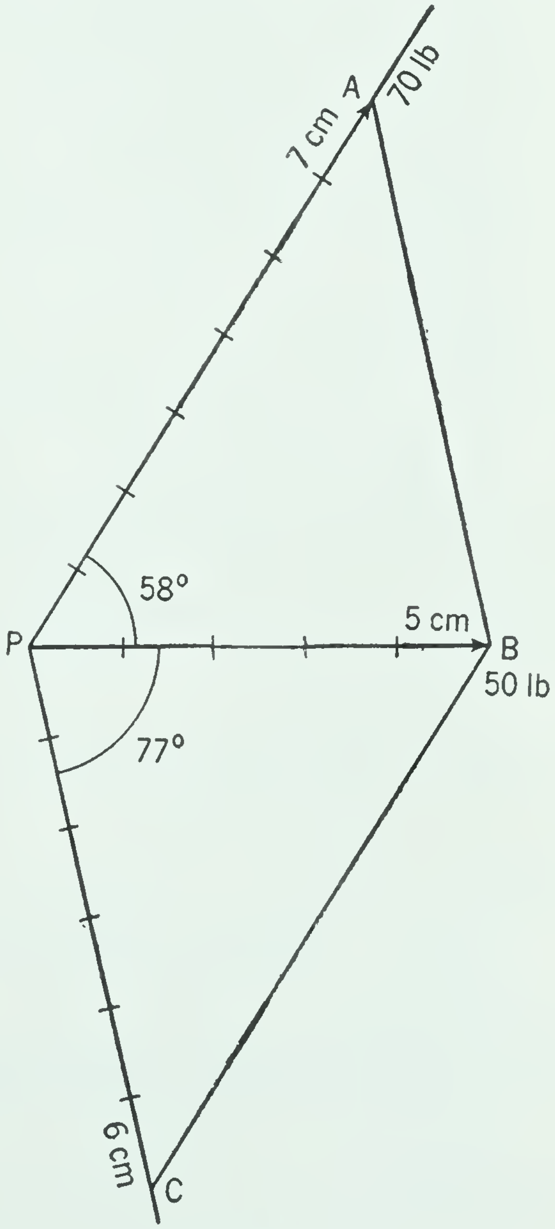


FIG. C–11.

D

Glossary

Absolute temperature: Temperature measured on a scale, the zero point of which is 273° below zero on the centigrade scale. To convert centigrade to absolute, add 273°.

Absolute zero: The zero point on the absolute temperature scale; it is the point of total absence of heat.

Absorb: To suck up, imbibe, or take in.

Acceleration (ăk-sĕl′ẽr-ā′shŭn): The rate of change of velocity.

Acidimeter (ăs′ĭ-dĭm′ē-tẽr): A special hydrometer for measuring the concentration of acids.

Adhesion (ăd-hē′zhŭn): The force of attraction between unlike molecules.

Adsorption (ăd-sôrp′shŭn): The condensation of gases on the surface of a solid.

Airfoil: Any surface, such as an airplane wing, aileron, or rudder, which is designed to obtain useful reaction, especially lift, from the air through which it moves.

Alcoholometer (ăl′kō-hŏl-ŏm′ē-tẽr): A special hydrometer for measuring the per cent of alcohol in a mixture of alcohol and water.

Alloy: A substance composed of two or more metals.

Aneroid (ăn′ẽr-oid): Without liquid.

Asbestos (ăs-bĕs′tŏs): A fibrous mineral that is neither flammable nor easily melted.

Atom: The smallest particle of an element, that retains all the properties of that element.

Babbitt (băb′ĭt): An antifriction alloy composed of antimony, tin, and copper. (Bearing metals commonly are made of lead and antimony.)

Ball bearing: A bearing that contains balls to reduce friction.

Bernoulli's principle: If the speed of a liquid passing through a tube increases at any point, the pressure of the liquid decreases at that point.

Bevel gear: A gear wheel whose teeth are cut at an angle other than a right angle to the plane in which the wheel revolves.

Boiling point: The temperature at which the vapor pressure of a liquid just exceeds the air pressure.

Bore: The interior diameter of a tube.

Boyle's law: When the temperature remains constant, the volume of any dry gas varies inversely with the applied pressure.

Brake drum: A revolving cylinder, attached to the wheel of a car, against the inside or outside of which the brake band presses.

Brake lining: A durable friction material used on brake bands to make friction against the brake drums on the wheels.

British thermal unit (B.T.U.): The unit of heat in the English system; it is the amount of heat necessary to raise the temperature of 1 lb. of water 1° F.

Brittleness: The property of a substance which allows it to be broken.

Buoyancy (boi′*ă*n-sĭ): The upward force which a fluid exerts upon a floating or a submerged body.

Caisson (kā′son): A watertight chamber within which underwater construction can be carried on.

Calibrate (kăl′ĭ-brāt): To graduate an instrument, or to verify its graduation.

Caliper (kăl′ĭ-pẽr): A graduated rule with one fixed and one sliding jaw.

Calorie: The metric unit of heat representing the amount of heat necessary to raise 1 gm. of water 1° C.

Cam (kăm): A projection on a revolving shaft for the purpose of changing up-and-down or to-and-fro motion into rotary motion, or vice versa.

Capillarity (kăp′ĭ-lăr′ĭ-tĭ): The action, due to surface tension and adhesive force, by which liquids are elevated or depressed in capillary tubes.

Capstan (kăp′st*ă*n): A wheel and axle used for hoisting the anchor of a ship.

Carburetor (kär′bū-rĕt′ẽr): A device for vaporizing gasoline, and for mixing the vapor with air.

Casing-head gasoline: Gasoline made from natural gas by low temperature and high pressure.

Catalyst (kăt′*ȧ*-lĭst): Any substance which changes the speed of a chemical reaction without itself being changed.

Center of gravity: That point in a body at which all its weight seems to be concentrated.

Center of moments: The point about which a lever in equilibrium is free to move.

Center of oscillation: *See* **Center of percussion.**

Center of percussion: That point at which a blow produces the least effect upon the point of suspension.

Centigrade: One hundred degrees.

Centigrade scale: The scale of a thermometer on which the freezing point of water is 0° and the boiling point is 100°.

Centimeter: 1/100 of a meter; it equals 0.4 inch.

Centrifugal (sĕn-trĭf′ū-găl): Pulling or reacting from the center.

Centripetal (sĕn-trĭp′ē-tăl): Directed or pulling toward the center.

C.G.S.: Centimeter-gram-second system of measurement, or the metric system.

Charles' law: If the pressure remains constant, the volume of a given mass of dry gas is directly proportional to the absolute temperature.

Chassis (sha′sē): The frame of an automobile to which the body and the wheels are attached.

Chemistry: That science which deals with chemical changes, and with the chemical composition of matter.

Chemical change: A change due to chemical combination or decomposition.

Clinical (klĭn′ĭ-kăl) **thermometer:** A self-registering thermometer for determining the temperature of a body, usually human.

Clockwise (klŏk′wīz′): Like the motion of the hands of a clock.

Clutch: A device which connects the engine shaft to the drive shaft.

Coefficient (kō′ĕ-fĭsh′ĕnt): A number used as a factor.

Coefficient of cubical expansion: The increase in unit volume when a solid is heated one degree. It is slightly more than three times the coefficient of linear expansion.

Coefficient of linear expansion: The increase in unit length of a solid when it is heated one degree.

Coefficient of superficial (sū′pĕr-fĭsh′ăl) **expansion:** The increase in unit area when a solid is heated one degree.

Coefficient of volume expansion: *See* **Coefficient of cubical expansion.**

Cohesion (kō-hē′zhŭn): The force of attraction between like molecules.

Combustion: A chemical reaction in which noticeable heat and light are produced.

Compensated (kŏm′pĕn-sāt′ĕd): Having opposing forces balanced.

Compound bar: A bar made of two metal strips of unequal coefficients of expansion, which are riveted together.

Compound engine: A steam engine in which the exhaust steam from the first cylinder is allowed to expand into a second cylinder. This is called double expansion; some engines are triple- or quadruple-expansion.

Compound machine: Any combination of two or more simple machines.
Conduction (kŏn-dŭk′shŭn): Transmission of heat from molecule to molecule.
Conductor (kŏn-dŭk′tẽr): Any material through which heat or electricity can pass easily.
Convection (kŏn-vĕk′shŭn): Transmission of heat by the intermingling of the heated masses.
Corliss valves: Valves used in large steam engines, which open and close by rocking or turning slightly in the valve seats.
Corrugated (kŏr′o͝o-gāt′ĕd): The state of being formed in furrows or folds.
Counterclockwise (koun′tẽr-klŏk′wīz′): Revolving in the direction opposite to that followed by the hands of a clock.
Cracking process: The process of breaking high molecular weight hydrocarbons into lighter and more volatile ones.
Critical pressure: The pressure needed to liquefy a gas at its critical temperature.
Critical temperature: The temperature to which any gas must be cooled before it can be liquefied by pressure.
Curvilinear (kûr′vĭ-lĭn′ē-ẽr) **motion:** Motion along a curved line.
Cylinder: A tubular chamber in an engine or other machine.

Dead center: The position of the crank of an engine when it is in a straight line with the connecting rod.
Density: Weight per unit volume.
Destructive distillation: The process of dry-distilling a solid, such as soft coal or wood, from which many products are obtained.
Differential (dĭf′ẽr-ĕn′shăl): A set of gears that allows for the difference in speed of the rear wheels of a car at certain times; for instance, when turning a corner.
Diffusion (dĭ-fū′zhŭn): Intermingling of molecules or atoms without regard to weight.
Direct proportion: Two quantities are in direct proportion to each other when an increase or decrease in one of them produces a corresponding increase or decrease in the other.
Distillation: The process of converting a liquid into a vapor, then condensing the vapor.
Distributor (dĭs-trĭb′ū-tẽr): A device used to distribute the spark to the engine cylinders in the proper sequence and at exactly the right time.
Drag: The reacting force of an airplane to the forward drive of the propellers.
Ductility (dŭk-tĭl′ĭ-tĭ): The property of a substance which permits it to be drawn into a wire.

Eccentric (ĕk-sĕn′trĭk): A wheel that rotates about a point which is not its center; it is used to change circular motion into back-and-forth or up-and-down motion or vice versa.

Efficiency (ĕ-fĭsh′ĕn-sĭ): The ratio of the useful work accomplished to the total work expended.

Elastic constant: The stress divided by the strain.

Elastic limit: The point at which the deformation of an object begins to become permanent.

Elasticity (ē′lăs-tĭs′ĭ-tĭ): The property of a body which causes it to resist deformation, and subsequently to recover its original shape and size.

Elasticity of compression: The elasticity of volume; for example, the squeezing of a tennis ball.

Elasticity of extension: A distortion of length; for example, the stretching of a rubber band.

Elasticity of flexure (flĕk′shĕr): The elasticity of bending; for example, the bending of a strip of steel.

Elasticity of torsion (tôr′sh*ŭ*n): The elasticity of twisting; for example, a coiled spring.

Elinvar (ĕl′ĭn-vär): A steel alloy used in making hair springs and balance wheels for watches.

Emulsion (ē̍-mŭl′sh*ŭ*n): A mixture in which small drops of one liquid are suspended in another liquid; for example, oil in water.

Endothermic (ĕn′dō̍-thûr′mĭk) **reaction:** A chemical reaction which absorbs heat.

Energy: Capacity for work.

Equilibrant (ē̍-kwĭl′ĭ-br*ă*nt): A single force that prevents motion.

Equilibrium (ē′kwĭ-lĭb′rĭ-*ŭ*m): A state of balance between opposing forces.

Ethyl gasoline: A gasoline which contains small quantities of tetraethyl lead and of ethylene bromide.

Evaporation (ē̍-văp′ō̍-rā′sh*ŭ*n): Changing from a liquid to a gas or vapor.

Exothermic (ĕk′sō̍-thûr′mĭk) **reaction:** A chemical reaction which liberates heat energy.

Expansion (ĕks-păn′sh*ŭ*n): The resulting increase in volume of a heated substance.

Fahrenheit (făr′*ĕ*n-hīt) **scale:** The thermometer scale on which the freezing point of water is 32° and the boiling point 212°.

Firedamp: Methane gas mixed with air in a coal mine.

Fire-tube boiler: A steam engine boiler in which the flames are drawn through long horizontal tubes surrounded by water.

Flash point: The kindling temperature of flammable substances such as gasoline and alcohol.
Fluid friction: Friction between molecules of a fluid such as oil.
Flywheel: A heavy-rimmed wheel attached to the crankshaft of an engine or some other machine.
Foot-pound: Unit of work and of energy; the amount of work done in exerting a force of 1 lb. through a distance of 1 ft.
Force: A push or pull.
F.P.S.: Foot-pound-system of measurement; this is the English system.
Fractional distillation: The process of separating a mixture of two or more liquids by means of the differences in their boiling points.
Freezing point: The temperature at which a liquid changes to a solid.
Friction (frĭk′shŭn): The resistance to any force trying to produce motion.
Fulcrum (fŭl′krŭm): The support about which a lever turns.
Fusion (fū′zhŭn): The process of changing a solid into a liquid; melting.

Gear: A wheel with teeth which fit into the teeth of another similar wheel.
Gear train: A combination of two or more cogwheels.
Grade: The ratio of the height of an incline to its length.
Gram: The unit of weight in the metric system; it is the weight of 1 ml. (or cc.) of water at 4° C.; it is equal to 0.0353 oz.
Gram-centimeter: A unit of work and energy; the work accomplished in exerting a force of 1 gm. through a distance of 1 cm.
Gravitation (grăv′ĭ-tā′shŭn): The force of attraction between two bodies.
Gravity pressure: Pressure caused by the weight of liquids.
Gusher (gŭsh′ẽr): An oil well with a large natural flow.
Gyroscope (jī′rō-skōp): An apparatus consisting of a heavy-rimmed flywheel free to rotate at great speed on bearings contained in a ring, so as to have freedom of movement in one or more directions.

Hardness: The resistance of molecules of a substance to separation by force.
Head of water: The difference in levels of communicating pipes; or the depth of water in a lake used to obtain power.
Heat: A form of energy. The heat of a body depends upon the sum total of all the kinetic energies of its molecules.
Heat of condensation: The number of calories of heat given off when 1 gm. of a vapor condenses to a liquid without any change in temperature; numerically it is the same as heat of vaporization.

Heat of fusion: The number of calories needed to melt 1 gm. of a substance without increasing its temperature.
Heat of vaporization: The heat required to vaporize 1 gm. of a substance without changing its temperature.
Helical (hĕl′ĭ-kă̇l) **gear:** A cogwheel whose teeth are cut in spiral form.
Henry's law: The amount of gas that can be absorbed, or dissolved, in a liquid is directly proportional to the pressure.
Hooke's law: Within the limits of perfect elasticity, strain is directly proportional to stress.
Horsepower: 550 ft.-lb. of work per second.
Hydraulics (hī-drô′lĭks): The science of fluids in motion and fluid pressure.
Hydrometer (hī-drŏm′ē̇-tẽr): An instrument for finding the specific weight of a liquid by the flotation method.
Hydrostatic (hī′drō̇-stăt′ĭk): Pertaining to liquids at rest.

Immiscible (ĭ-mĭs′ĭ-b'l): Not miscible.
Impenetrability (ĭm-pĕn′ē̇-tră̇-bĭl′ĭ-tĭ): The inability of two substances to occupy the same space at the same time.
Incandescent (ĭn′kăn-dĕs′ĕ̇nt): Glowing with heat.
Inclined plane: A sloping surface.
Inertia (ĭn-ûr′shȧ): Disinclination of matter to move or to stop moving.
Input: The energy put into a machine.
Insulator (ĭn′sū̇-lā′tẽr): A substance that does not conduct heat.
Internal-combustion engine: An engine which burns fuel inside itself, as in the cylinder of a gasoline engine.
Invar (ĭn-vär′): An alloy of iron, nickel, and carbon, which has a low coefficient of expansion.
Inverse proportion: Two quantities are inversely proportional when an increase in one of them produces a corresponding decrease in the other.

Jackscrew: A screw with a high mechanical advantage, used for lifting buildings and other heavy objects.

Kilogram (kĭl′ō̇-grăm): 1000 gm.; it equals 2.2 lb.
Kilometer (kĭl′ō̇-mē′tẽr): 1000 m.; it equals 0.6 mi.
Kilowatt: 1000 watts.
Kindling temperature: The lowest temperature at which a substance takes fire.
Kinetic: Moving.

Kinetic energy: Energy of motion.
Kinetic theory of matter: The theory which assumes that the molecules of all matter are in constant motion.
Knee-action: A method of obtaining independent suspension of car wheels.

Lactometer (lăk-tŏm′ē-tẽr): A special hydrometer used to determine the richness of milk.
Law: A statement of natural processes and phenomena; it is generally capable of laboratory proof.
Law of gravitation: Every body attracts every other body with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.
Law of heat exchange: The total number of heat units lost by a warm substance equals the total number of heat units gained by a cooler substance when the two substances are in contact with each other.
Law of rebound: For a perfectly elastic ball the angle of rebound equals the angle of incidence.
Lever (lĕv′ẽr; lē′vẽr): A bar working on a pivot called a fulcrum.
Lift: The vertical reaction to the wind pressure on an airfoil.
Liter (lē′tẽr): 1000 cc.; it is equal to 1.057 liquid quarts.
Lubricant (lū′brĭ-kănt): A substance such as oil used to make surfaces smooth and slippery to reduce friction.

Machine: A device to transfer or transform energy.
Malleability (măl′ē-ȧ-bĭl′ĭ-tĭ): The property of a substance which permits it to be hammered or rolled into thin sheets.
Manometer (mȧ-nŏm′ē-tẽr): A mercury type of pressure or vacuum gauge.
Mass: The quantity of matter which a body contains.
Matter: Anything that takes up room.
Mechanic (mē-kăn′ĭk): A person who knows how to construct, repair, and use machines.
Mechanical advantage: The advantage of force or speed gained by the use of a machine.
Mechanical equivalent of heat: One B.T.U. equals 778 ft.-lb. of work. In the metric system one calorie equals 427 gram-meters of work.
Mechanics: The science of the construction and use of machines.
Melting point: The temperature at which a solid changes to a liquid.
Meter: The metric system's unit of length; it is equal to 39.37 inches.

Micrometer (mī-krŏm′ė-tẽr): An instrument used for measuring minute distances.

Meniscus (mė-nĭs′k*ŭ*s): The curved part of a liquid surface.

Miscible (mĭs′ĭ-b’l): Mutually soluble as applied to two liquids.

Mobile (mō′bĭl): The property of a liquid to flow easily.

Molecule (mŏl′ė-kūl): A particle composed of two or more atoms, either of different elements or the same element.

Moment of force: The effectiveness of a force in producing motion; such effectiveness depends upon the magnitude of the force and the length of the lever arm upon which it acts.

Momentum (mȯ-mĕn′t*ŭ*m): The quantity of motion.

Neutral equilibrium (ē′kwĭ-lĭb′rĭ-*ŭ*m): The property of certain objects which enables the center of gravity to remain neutral; that is, neither raised nor lowered, even though the object itself is overturned.

Octane number: A term used to measure the antiknock property of gasoline.

Oscillation (ŏs′ĭ-lā′sh*ŭ*n): A backward-and-forward motion, or vibration.

Osmosis (ŏs-mō′sĭs): Diffusion through membranes.

Output: The useful energy obtained from a machine.

Oxidation (ŏk-sĭ-dā′sh*ŭ*n): That process by which oxygen unites with some other substance.

Pendulum (pĕn′dū-l*ŭ*m): A body so suspended that it can swing to and fro about a horizontal axis.

Physical change: A change in which the identity of a substance is not lost, in which there is no change in chemical composition.

Physics: That science which deals with matter and energy, and also with physical changes in matter.

Pinion (pĭn′y*ŭ*n) **gear:** A spur gear, which is in mesh with another cogwheel which has a greater number of teeth.

Piston: A solid cylinder that fits the tubular chamber of an engine, or other machine, gas tight; however, it may be driven back and forth by gas, steam, or other pressure.

Plastic: Capable of being molded, pressed, or hammered into a desired shape.

Pneumatics (nū-măt′ĭks): That branch of physics that deals with the mechanical properties of gases.

Polymer (pŏl′ĭ-mẽr) **gasoline:** Gasoline made from hydrocarbons which were gases, such as methane.

Potential (pō̇-tĕn′shăl) **energy:** Energy at rest, or energy of position.
Power: The rate of doing work.
Pressure: Force acting on unit area.
Pulley: A wheel with a grooved rim in which a rope can run; it is used to lift weights or to change the direction of a force.
Pycnometer (pĭk-nŏm′ē̇-tẽr): A bottle used for determining the specific weight of a liquid.

Radiation (rā′dĭ-ā′shŭn): Transmission of heat energy by rays or waves.
Reaction: To every action there is an equal and opposite reaction.
Reciprocating (rē̇-sĭp′rō̇-kāt′ĭng): Backward-and-forward, or to-and-fro, as distinguished from rotary.
Rectilinear (rĕk′tĭ-lĭn′ē̇-ȧr) **motion:** Motion in a straight line.
Regelation (rē′jĕ-lā′shŭn): Melting under pressure and freezing again as pressure is reduced.
Relative humidity: The per cent of water vapor in the air, as compared with the amount the air could hold at a given temperature.
Resultant (rē̇-zŭl′tănt): A single force that can be substituted for two or more forces without altering the effect.
Roller bearing: A bearing in which rollers turn between a wheel, or shaft, and its support to reduce friction.
Rolling friction: The friction between a surface and a roller or wheel.
Rotary (rō′tȧ-rĭ) **motion:** Circular motion, turning, as a wheel on its axis.
Rotor (rō′tẽr): The rotating part of a turbine.

Safety factor: The ratio of the strength of a material to the maximum load which it will have to support.
Science: Classified knowledge.
Screw: A simple machine consisting of an inclined plane wound around a cylinder.
Slide valve: A valve in the steam engine which moves back and forth to let steam into first one end of the cylinder, then the other; at the same time it regulates the escape of the exhaust steam.
Sliding friction: Friction caused by two solids sliding over each other.
Solid friction: Friction between two solid surfaces.
Solute (sŏl′ūt): Any substance which is dissolved in a solution.
Solution (sō̇-lū′shŭn): A liquid or solid which contains the uniformly scattered molecules of one or more liquids or solids.
Solvent (sŏl′vĕnt): A substance, such as water, which will dissolve another substance.
Specific heat: The number of calories needed to raise the temperature of 1 gm. of a substance 1° C.

Specific volume: One divided by the specific weight of a substance; in the metric system, it is the volume of the body in cc. that is needed to weigh 1 gm.

Specific weight: The weight of a substance compared with the weight of an equal volume of the standard. (The standard for liquids and solids is water; for gases it is air or hydrogen.)

Spontaneous (spŏn-tā′nē-*ŭ*s) **combustion:** A combustion which originates in a slow oxidation that develops faster until the kindling temperature is reached, resulting in burning.

Sprocket (sprŏk′ĕt) **wheel:** A type of cogwheel of which the cogs or sprockets are made to engage with the links of a chain.

Spur gear: The simplest form of toothed wheel or cogwheel.

Stable equilibrium (ē′kwĭ-lĭb′rĭ-*ŭ*m): The condition of a body when it cannot be overturned without first raising its center of gravity.

Standard pressure: 760 mm. of mercury.

Standard temperature: 0° C.

Stator (stā′tẽr): The stationary case or base of a turbine.

Steam chest: The steam compartment of a steam engine, that covers the slide valves and cylinder openings.

Strain: The change or distortion produced by a stress upon a body; for example, the stretching of a spring.

Stress: A force which acts upon a body, such as a spring, and tends to distort it.

Surface tension: The contractile property of liquid films.

Suspension (sŭs-pĕn′sh*ŭ*n): A very finely divided insoluble solid, stirred through a liquid and slow in settling.

Temperature (tĕm′pẽr-*ȧ*-tūr): Degree of heat.

Tempering: Heat treatment given to certain metals, such as steel, to make them tougher and less brittle.

Tenacity (tē-năs′ĭ-tĭ): Resistance to being pulled apart.

Tensile (tĕn′sĭl) **strength:** The force needed to break a rod or wire of that material whose cross-section area is unity, one square inch, for example.

Theory (thē′ō-rĭ): An explanation of natural phenomena partially verified, but not usually capable of laboratory proof.

Thermograph (thûr′mō-grȧf): A self-registering thermometer.

Thermostat (thûr′mō-stăt): A device to regulate temperature.

Total force: The product of average pressure times the area.

Trajectory (tr*ȧ*-jĕk′tō-rĭ): The curve which a body, as a missile, describes as it moves through space.

Transmission (trăns-mĭsh′*ŭ*n): The part of an automobile involved in transmitting power from the engine to the rear wheels.

Transmission gears: Sets of gear wheels used to vary the speed of a car and to reverse the car.
Turbine (tûr′bĭn): A rotary motor driven by steam or water.

Ultramicroscope (ŭl′trȧ-mī′krō-skōp): An instrument used to see light reflected from particles too small to be seen by an ordinary microscope.
Unbalanced: State of having a greater force on one side of an object than exists on the opposite side.
Unstable equilibrium (ē′kwĭ-lĭb′rĭ-*ŭ*m): The condition of a body when its center of gravity is directly above the sharp point of support.

Vaporization (vā′pẽr-ĭ-zā′sh*ŭ*n): Changing from a liquid to a vapor.
Velocity (vē-lŏs′ĭ-tĭ): The rate of motion.
Venturi (vĕn-tōō′rē) **tube:** A tube which is constricted for the purpose of increasing the velocity of a fluid at the point of the constriction.
Vernier (vûr′nĭ-ẽr): A short scale made to slide along the divisions of a graduated instrument to measure parts of divisions.
Viscous (vĭs′kŭs): The property of a liquid to flow slowly, like tar.

Water-tube boiler: A steam-engine boiler in which the flames play all around a number of pipes filled with water, and also against the bottom of the boiler itself.
Watt (wŏt): The metric unit for measuring power; it equals about 10,200 gram-centimeters per second, or 1/746 H.P.
Wedge: A double inclined plane.
Weight: The measure of the earth's attraction for a body.
Welding: Uniting of similar metals by heating them to the melting point and joining them.
Wheel and axle: A simple machine composed of a crank or wheel attached to a bar or axle.
Windlass (wĭnd′l*ȧ*s): A type of wheel and axle used for hoisting or bowling by turning a crank so as to wind up a rope attached to a weight.
Work: A force that moves a resisting body does work.
Worm gear: A machine which is a combination of a screw and helical gear.

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